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Addressing Irrigation Aquifer Depletion

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Cover photos: Top: *Panoramic view of the Ukiah Valley Groundwater Basin, California*, Credit: Maritza Flores Marquez; Bottom Left: *Aerial view of Haxtun, Colorado*, Credit: William A. Cotton; Bottom Right: *Aerial view of agricultural activities in the Haxtun, Colorado area using water supplied by the Ogallala Aquifer*, Credit: William A. Cotton
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Addressing Irrigation Aquifer Depletion

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Addressing Irrigation Aquifer Depletion: Introduction

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The Food and Agriculture Organization of the United Nations (FAO) estimates that food production must be increased 70% (from 2009 levels) in order to feed an additional 2.3 billion people by 2050 (FAO 2009). Irrigated cropland is extremely important to global food security. According to FAO (2016), although irrigated cropland currently occupies only about 20% of the total agricultural area worldwide, it supplies roughly 40% of the total yield (i.e. 3.6 times that of dryland). Groundwater is an extremely important source of irrigation water. An estimated 38% of irrigated areas depend on groundwater (Siebert et al. 2010) and in the U.S., groundwater supplies 43% of the irrigation water (Maupin et al. 2014). At the same time, an increasing number of countries and regions are reaching alarming levels of water scarcity. According to NASA satellite data, 13 of the largest 37 aquifers in the world are considered significantly distressed (Richey et al. 2015). Severe aquifer depletion evident in the Ogallala Aquifer, California's Central Valley, the Mississippi Delta, and Arizona's alluvial basins (Konikow 2013) threaten food production in the U.S. How will we meet growing food demands and the water needs of growing populations in these regions with declining aquifers? How do we prolong, sustain, or restore these aquifers? When restoration is not possible, how do we best support the conversion to dryland or grazing systems? This JCWRE special issue examines new technologies, cropping system management practices, decision support tools, incentives and policies to sustain food production, rural communities, and ecosystem services in these critical regions. In particular, recent research advances from the decades long USDA-ARS funded Ogallala Aquifer Program, recently funded USDA-NIFA Ogallala Water Coordinated Agricultural Project, and regional efforts in California and the Mississippi Delta are discussed.

Brauer et al. describe the research and education efforts of the Ogallala Aquifer Program conducted over the last decade and a half. USDA-ARS laboratories in Bushland and Lubbock TX, with university partners at Kansas State University, Texas A&M AgriLife Research and Extension Service, Texas Tech University and West Texas A&M University are developing and evaluating water management strategies and technologies to reduce water withdrawals for irrigation by 20% in 2020 (compared to 2012) and increase the productivity and profitability of dryland cropping systems, including developing best management practices for production of high value and alternative crops for both dryland and irrigated systems. This consortium is also working to improve the understanding of hydrological and climatic factors affecting water use and agricultural profitability and determining the impacts of alternative water withdrawal/use policies on the economic viability of the agriculture industry of the Southern Ogallala Aquifer region.

These efforts are extremely important, particularly with the warming trends documented by Lin et al. resulting in increased evapotranspiration loss, soil moisture stress, and associated management challenges in Kansas. This, coupled with declining water levels in the Ogallala Aquifer and increasing restrictions on pumping are challenging the production of corn and other crops. Xue et al. found in their review of long-term production and corn management practices that yields and water use efficiency have increased due to advances in corn genetics and irrigation technologies, and recommended continued research to improve grain quality, crop drought tolerance, and adoption of new technologies to sustain production in the High Plains.

Water use-yield relationships are important for efficient water management (Siahpoosh et al. 2012) and models such as the Kansas Water Budget (KSWB) and Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) are important tools to assess these relationships. Moberly et al. evaluated the predictive accuracy of the KSWB model for crop water use and grain sorghum and winter wheat productivity, grown in a range of crop sequences. They found that the Kansas Water Budget model provided a useful analytic framework for predicting water supply constraints to grain production, but poorly predicted yield response for either grain sorghum or winter wheat. Adhikari et al. used the DSSAT-CSM model to simulate the long term cotton lint yield and seasonal crop ET and found it useful for scheduling ET-based irrigation management practices in the Texas High Plains and estimating future ET for other modeling experiments.

In addition to these models, groundwater models that not only capture regional hydrogeologic characteristics but also human-hydrologic-climate interactions are crucial for guiding future water management and policy planning endeavors. A conceptual modeling framework built on this premise was applied by Uddameri et al. to a current regional-scale groundwater modeling study in the Southern High Plains where the lack of groundwater production data is a major limiting factor. To identify alternative approaches to fill this critical data gap and properly parameterize the model, they evaluate the importance of surface water groundwater interactions, determine whether explicit coupling of watershed and groundwater models is warranted, and assess limitations in simulating human-aquifer interactions. The study demonstrated the utility of several simple "first-cut" analysis techniques to evaluate groundwater interactions with other interconnected systems.

Golden and Guerrero evaluate the likely economic impacts associated with the implementation of LEMAs, Local Enhanced Management Areas authorized by the 2012 Kansas Legislature. Under this Kansas water law, groundwater management districts have the authority to initiate a voluntary process to develop a conservation plan meeting local goals. Results suggest that the LEMA framework of groundwater management will provide benefits to both the agricultural producer and rural communities. However, Golden and Guerrero note that LEMA adoption may only result in short-lived reductions in groundwater consumption with water saved today eventually being used and the water resource exhausted.

Similarly, in 2014, the Sustainable Groundwater Management Act was enacted in California to reform groundwater management and ensure groundwater is managed sustainably. To help groundwater managers create some of the baseline measures needed to develop a groundwater sustainability plan required by this Act for medium and high priority basins, Flores Marquez et al. introduce a novel method for development of a water budget and present the implementation of this method in the Ukiah Valley Groundwater Basin. Results indicate that because the groundwater basin is not experiencing a decrease in groundwater storage or a lowering of the water table, the groundwater sustainability agency is uniquely positioned to focus on proactive maintenance of current conditions when constructing their sustainability plan.

In the final paper, Reba et al. describe key research efforts in the Lower Mississippi River Basin, an internationally-important region of intensive crop production heavily reliant on the Mississippi River Valley Alluvial Aquifer for irrigation. This region too is facing aquifer depletion and exploring innovative methods to address this issue. Reba et al. investigated innovations in rice irrigation, on-farm water storage, and managed aquifer recharge as means to reduce the on-going decline of this economically and ecologically important alluvial aquifer. They found that collaborative efforts to improve rice irrigation management as part of the Rice Stewardship Partnership effectively reduced the amount of water applied on nearly 30,000 hectares. Their inventory of on-farm reservoir tailwater recovery systems showed that significant investments have been made as part of efforts and supports the potential for surface water storage in critical groundwater areas. Finally, the novel test of managed aquifer recharge described will be used as the basis for further testing in areas where large-scale surface water projects are unlikely.

As this special issue demonstrates, significant efforts and advances are ongoing throughout the U.S. and globe to ensure food and water needs are met into the future. However, continued research is needed to improve irrigation efficiency, crop genetics, cropping systems, and our understanding of the climate, hydrology, water use, and policy impacts. As noted by Golden and Guerrero, adoption may only result in short-lived reductions in groundwater consumption with water saved today eventually being used and production ultimately converted to dryland. Efforts today to improve dryland production will go a long way to ensuring food for future generations.

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Kevin L. Wagner is the Director of the Oklahoma Water Resources Center and holds the Thomas E. Berry Professorship in Integrated Water Research and Management. He provides leadership and administration of the Center's water programs, leads Center efforts to increase engagement with the water resources community across Oklahoma and the nation, and facilitates development of inter-disciplinary teams to address high priority water resources issues. Wagner has more than 20 years of experience in watershed assessment and planning, stakeholder engagement and conservation practice research and education. He may be contacted at kevin.wagner@okstate.edu.

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Ogallala Aquifer Program: A Catalyst for Research and Education to Sustain the Ogallala Aquifer on the Southern High Plains (2003-2017)

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Abstract: The Ogallala Aquifer Program (OAP) was created in 2003 with support from Congressmen from Kansas and Texas. The OAP is a research-education consortium seeking solutions from problems arising from declining water availability from the Ogallala Aquifer in western Kansas and the Texas High Plains. The consortium is led by the Agricultural Research Service (ARS) laboratories in Bushland and Lubbock, TX, and the university partners are Kansas State University, Texas A&M AgriLife Research and Extension Service, Texas Tech University, and West Texas A&M University. The OAP has provided over $40 million to support research and education activities. About half of these funds were used to support permanent ARS scientists and ARS hired post-docs. The other half were used by university scientists to supplement on-going projects by providing support for supplies, sample analyses, temporary employees, etc. Initially, OAP activities were focused on seven priorities. In 2013, four objectives replaced the original seven priorities. A fifth priority was added in 2017. The current objectives are: 1) Develop and evaluate water management strategies and technologies that could reduce water withdrawals for irrigation by 20% in 2020 compared to 2012; 2) Develop and evaluate management strategies and technologies that would increase the productivity and profitability of dryland cropping systems; 3) Improve the understanding of hydrological and climatic factors that affect water use and agricultural profitability; 4) Determine the impacts of alternative water withdrawal/use policies on the economic viability of the agriculture industry of the Southern Ogallala Aquifer Region; and 5) Develop best management practices for production of high value and alternative crops for both dryland and irrigated systems. The objectives of the program and distribution of resources are decided by an executive committee with a member from each of the four universities, two from ARS, one from Bushland, and the other from Lubbock. Proposed projects that utilize resources from more than one participating institution, leverage existing resources, and address the stated objectives are more likely to be provided support. The impact of the OAP on research directed at agriculture on the High Plains has been recognized by three prestigious awards.

Keywords: *irrigation technology, irrigation scheduling, water conservation, economic impacts*

The objective of this article is to provide an overview of the Ogallala Aquifer Program (OAP) and to examine successes and failures that the program has experienced to date. The OAP was initiated in 2002 to address problems resulting from declining water levels in the Ogallala Aquifer. The program is a research-education consortium consisting of the Agricultural Research Service-U.S. Department of Agriculture (ARS-USDA) locations at Bushland and Lubbock, Texas, and four universities, Kansas State University, Texas A&M University, Texas Tech University, and West Texas A&M University. The alternative titles of the OAP have been modeled after its first Current

Research Information System (CRIS) project title: "Sustaining rural communities through new water technologies."

Background

The Ogallala Aquifer is located in the U.S. Great Plains (Fig. 1) and extends from the southern portion of the Texas High Plains and eastern New Mexico, northward through the panhandle areas of Texas and Oklahoma, into western Kansas and eastern Colorado, to Nebraska and southern South Dakota and eastern Wyoming, covering 173,000 square miles (Zwingle 1993). As such, the Ogallala Aquifer is the largest fresh water aquifer in the U.S. The saturated thickness of the aquifer, which comprises the interval between the water table of the aquifer and the base of the aquifer, ranges from 0 to 1200 feet and averages 200 feet (Fig. 1). The thickest portions of the saturated zone of the aquifer are located in Nebraska, and in the panhandle areas of Texas and Oklahoma into southwestern Kansas. The water-bearing formation of the Ogallala Aquifer is essentially "fossilized water", meaning that there is no longer a connection to the source of the water bearing materials and that recharge is limited to deep percolation and interactions between surface bodies and the aquifer. South of the Kansas-Nebraska state line, there are few rivers that transverse the U.S. Great Plains above the Ogallala Aquifer. Therefore, recharge is limited to deep percolation. Deep percolation rarely occurs because potential evaporation greatly exceeds rainfall (Baumhardt et al. 2010). On the Texas High Plains, there is an on-going debate as to the significance of playas, sites of lower elevation that inundate when heavy rainfall produces runoff, to recharge (Gitz and Brauer 2016). On the Texas High Plains, the best estimates for recharge outside of playas is that rain falling today will reach the

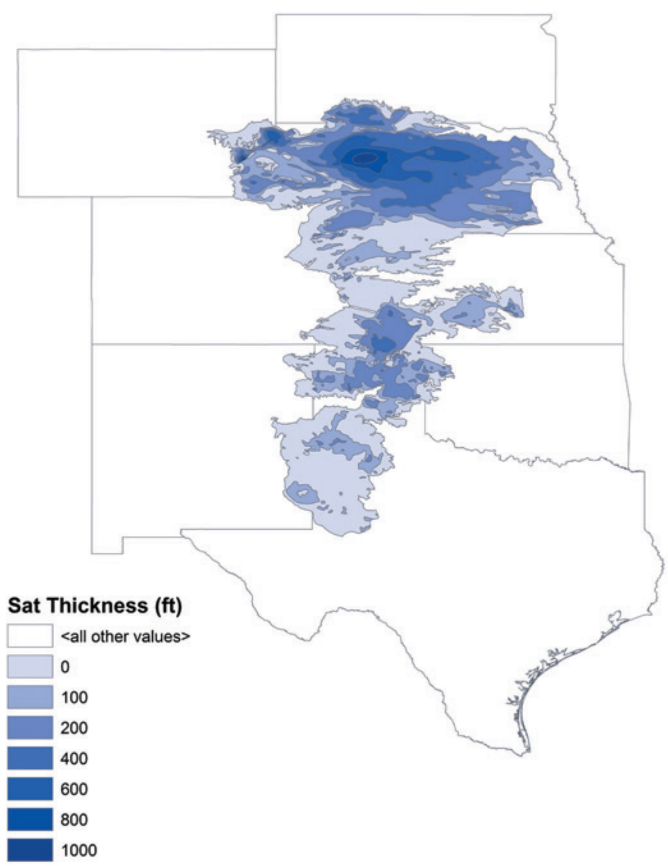

Figure 1. Saturated thickness in the Ogallala Aquifer prior to the development of widespread irrigation. Legend is in the figure. Figure is based on data from McGuire (2009).

aquifer in no sooner than 1,000 years. North of the Kansas-Nebraska border, rivers traversing the Great Plains are more numerous, and the depth to the top of the aquifer tends to be shallower. Therefore, recharge in the northern region of the aquifer is estimated to be at least 10 times faster.

Water from the Ogallala Aquifer has contributed greatly to the agricultural output of the Great Plains. A great increase in irrigation in the Great Plains occurred during the post-World War II era. By 1959, total irrigated cropland acreage was approximately 7 million acres. By 1978, irrigated cropland had increased to approximately 13 million acres. Irrigated acreage declined by approximately 20% by the late 1980s (Kromm and White 1992). Withdrawals greatly exceeding rates of recharge have resulted in lower well yields, deeper water tables, and reduced saturated thickness. Despite declines in irrigated acres, irrigation use still accounts for nearly 90% of the groundwater withdrawals in many areas over the Ogallala Aquifer. Aquifer depletion rates of 1 to 3 feet annually are commonplace in areas of irrigated agriculture. Although it has been estimated that only 10% of the water in the Ogallala Aquifer has been withdrawn (Gollehon and Winston 2013), the depletion is not constant across the aquifer. In many areas of the aquifer, especially in the southern portion of the Texas High Plains, eastern New Mexico, northwestern Kansas, and eastern Colorado, the saturated thickness has been reduced by at least 40% of pre-development levels (National Research Council 1996). Steward and Allen (2015) estimated that peak withdrawal rates for Texas occurred in 1999, and in 2010 for Kansas.

The current state of ground water utilization in the Great Plains is a reflection of economic, social, and political factors. The primary reason that the underground water resources in the Great Plains are being used at a high rate is that the revenues stemming from their current use are greater than the associated cost of extraction. Current withdrawals also increase farm and regional economic stability and reduce producer risks. However, current rates of withdrawals from the aquifer cannot be sustained in many areas of the Great Plains. For this reason, the sustainability of this resource and its associated economic consequences needs to be better understood.

Funding and Congressional Actions

In 2001-2002, representatives from ARS (Dr. Nolan Clark, Laboratory Director at Bushland, TX and Dr. Dan Upchurch, Laboratory Director at Lubbock, TX), Kansas State University (Dr. Bill Hargraves), Texas A&M University (Dr. Alan Jones), and West Texas A&M University (Dr. Jim Clark) drafted an initiative for consideration by the Congressional appropriation committees to provide funding for a research-education consortium that would become the OAP. Simultaneously, Texas Tech University was preparing a similar proposal with Dr. Sukant Misra acting as the point person. When the congressional delegation from Texas learned of the two potentially competing, they instructed the representatives from the two groups to draft a joint proposal, which occurred.

In 2002, reports for the fiscal year (FY) 2003 from both the House and Senate appropriation committees included funds to initiate the OAP. The Director of ARS' Southern High Plain Area, Dr. Chuck Onstad, was so confident that federal funds were forthcoming for the OAP that he provided $300,000 (Fig. 2) so that the organization of the scientists to participate in the OAP could begin. For FY2003, the U.S. Congress provided ARS-USDA with funding "for research into the complex nature of water availability, potential uses, and costs which will help determine future water policy in the Ogallala Aquifer Region". The two major objectives of the program were: "1) develop, evaluate, and disseminate information and technologies for water uses; and 2) provide scientifically sound data to water use planners and policymakers." Initially, Congress provided $670,613 and $223,537 to the Bushland and Lubbock, TX locations, respectively. In FY2004, Congress provided an additional $764,960 for the OAP, increasing the total to approximately $1.76 million (Fig. 2). ARS headquarter staff, under advisement from Congress, directed all of the OAP funds to reside at the Bushland location. However, Bushland was to provide the Lubbock location with sufficient funds for at least a 0.5 full time equivalent (FTE) research scientist. This scientist was to come from re-direction of current staff. ARS headquarters also directed ARS to hire 1.0 FTE research scientist at Bushland to

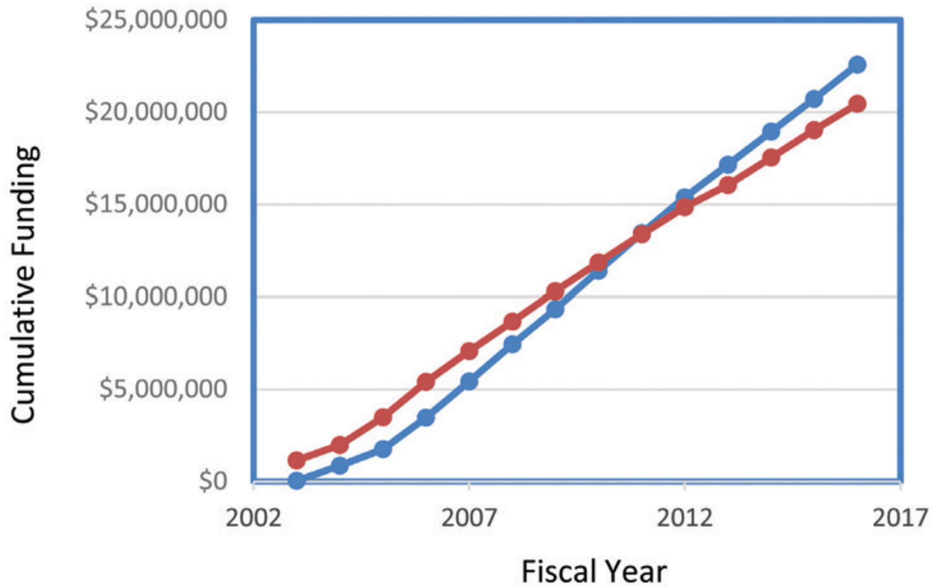

Figure 2. Cumulative funding for ARS (gray) and the sum of funding at four participating universities (black) from FY2003 to FY2016.

provide direct support for the OAP. In FY2005 and FY2006, Congress provided additional funds increasing the total OAP funding to approximately $3.6 million (Fig. 2). From these increased funds, the Bushland location was to hire two additional FTE research scientists, increasing Bushland OAP staff to 3.0 FTE.

In 2006, reports for FY2007 budgets from both the House and Senate appropriation committees provided even more funds for the OAP. These increases never came to the OAP. The attitude of Congress toward ear-marks changed during the 2006 congressional year. Congressionally directed ear-marks were defined by the Office of Management and Budget (OMB) as appropriations passed by Congress and approved by the President that directed specific funds to stated locations and for defined purposes. For example, a line item in an appropriation bill "directing $200,000 to Bushland, TX location for research directed towards better management of sorghum" would be an ear-mark. Congress passed and the President signed a continuing resolution for FY2007 providing funding at the FY2006 level so that the OMB could evaluate all line items to determine if they were congressional ear-marks.

The OMB evaluations of line items in previous year's budgets went beyond the language in the congressional appropriation bills. A major factor in the OMB's evaluations was: did the agency have in place sufficient controls to ensure that funds were directed towards federal priorities? The OMB determined that approximately 75% of the line items in ARS budgets were congressional ear-marks and recommended that these funds be re-directed to high priority projects. The OMB determined that funding for the OAP was not a congressional ear-mark because ARS had sufficient controls over the projects being funded to ensure that no cooperator was guaranteed a specific level of funding and that the projects addressed high priorities for the USDA.

From FY2007 to FY2014, funding for the OAP was designated as discretionary and therefore was relatively free from proposed re-directions in the President's proposed budget for the following year. It has been common for the President to propose re-direction of ear-marks and other congressional directed programs in the ARS budget to program areas that the executive branch deem of higher priority. This enables the administration to identify their research priorities with minimum increase in the agency's budget. Funding for the OAP was relatively constant from FY2007 to FY2011, except for minor changes for enhancements to governmental internet technology (IT) and increases in funds for federal salary to offset directed increases in employee's salaries (cost of living adjustments). In FY2012, the ARS was directed to close 10 locations. Unfortunately, location closure typically results in increased cost for retirements, etc. ARS headquarters ordered an across-the-board 30% reduction in outgoing funds including those OAP funds that supported research at the four participating universities. How that reduction was calculated is still a mystery to ARS OAP leadership. ARS headquarters ordered the outgoing funds to be approximately $1.15 million. The in-house portion of the OAP had to be decreased by $100,000 to reach the total reduction. The estimated cost for closure of the 10 locations was less than that estimated and therefore approximately $280,000 was provided at the end of FY2012 for cooperating universities. In total, the final reduction in OAP funding in FY2012 was approximately $170,000 or 5%.

The OAP did not fare as well in FY2013 when sequestration was imposed (Fig. 2), and OAP funding was reduced by approximately $400,000. In 2014, many recipients of outgoing funds from the ARS, including representatives from at least three of the four cooperating universities within the OAP, petitioned Congress for restoration of outgoing funds to FY2012 levels. The reports from the House and Senate appropriation committee for FY2014 included language for the ARS to restore outgoing funds to FY2012 levels. ARS' budget for FY2014 included an increase of $321,000 for the OAP. ARS' headquarters directions under advisement of Congress set outgoing OAP funding at approximately $1.4 million. Because the funding level was defined, the outgoing funds were designated as congressionally mandated, once again.

Total funding to the four universities was stable between FY2014 and FY2017. During this period, however, there was a change in OAP funding. The two CRIS projects associated with the OAP, one in Lubbock and one Bushland, are a part of ARS' National Program (NP) 211, Water Availability and Watershed Management. As such, both of these research projects developed a five-year research plan that was subjected to peer review in FY2016 and FY2017. To enhance long term research planning by ARS scientists, it was agreed that Bushland would transfer a portion of the in-house OAP to Lubbock. These funds would enable Lubbock scientists to develop long term research plans to meet the objectives of the NP211, as well as the OAP. In 2017, a permanent transfer of $400,000 from Bushland to Lubbock occurred so that Lubbock scientists can conduct their share of OAP research from 2017 to 2022.

In total, the OAP since its inception has provided over $40 million for research and education related to conservation of the Ogallala Aquifer (Fig. 2). Early in the program's history, the universities received more than half of the funds. After ARS hired the three authorized scientists, ARS' share of the funding has exceeded one-half.

Early Program Objectives and Management

Several meetings with potential participants and stakeholders were held in 2003. The six individuals mentioned in the previous section who drafted the appeal to Congress were responsible for identifying participants from the four universities and stakeholders that attended these meetings. These meeting were the basis of developing the initial program priority areas. In 2003, the priority areas were: 1) economic assessment of conservation practices and water policies; 2) region's hydrology and climatology; 3) integrated crop and livestock production; 4) irrigation and precipitation water management; 5) irrigation systems and technologies; and 6) technology transfer. These six areas were the basis of distributing FY2003 funds to research projects.

When funding for the OAP was certain, the six persons that were involved in the drafting of the joint congressional initiative formed what would become the program leadership. Shortly after, the leadership team was expanded to include the Research Leader (RL) of the Soil and Water Management Research Unit, Dr. Terry Howell, because OAP's CRIS project resides in this unit. Later, the leadership team was formally defined as the RLs of the Soil and Water Management Research Unit (ARS-Bushland), the Wind Erosion and Water Management Research Unit (ARS-Lubbock), the Laboratory Director (ARS-Bushland), and the PIs from the four universities. Decisions regarding program direction, etc. would be determined by consensus of the leadership team. The leadership team also included non-voting adjunct members, individuals either impacting the program or impacted by it. These members included Residence Directors of university research sites likely to be involved in the OAP including the Texas A&M AgriLife locations in Lubbock and Amarillo, the Director for agricultural experiment stations of the Kansas State University in western Kansas, and ARS' Area Director for Texas.

The program objectives were changed slightly in FY2004 by refining the objectives and adding a seventh objective. The revised objectives included: 1) estimate the economic impacts of water management activities; 2) improve water management, both irrigation and precipitation; 3) improve irrigation systems and technologies; 4) reduce the dependence on groundwater resources by developing integrated cropping systems; 5) develop methodologies for assessing groundwater resources of the Ogallala Aquifer (hydrology-climatology); 6) evaluate water use by concentrated animal feeding operations (CAFOs) and agricultural processing industries; and 7) develop information programs/technology transfer. These remained the priority areas until FY2014.

In FY2003, no official OAP Manager position existed, but the day-to-day management of the OAP was the responsibility of Dr. Nolan Clark, who also served as the Laboratory Director of the Bushland location, RL of the Renewable Energy and Manure Management Research unit, and as the primary scientist in the Renewable Energy Program. In FY2003 and FY2004, the program objectives for the OAP were clearly defined. The OAP leadership team approved a mechanism by which each priority area would have a team with a designated leader and two to three advisers. The OAP leadership would designate a target funding level for each priority area and the priority area team would recommend projects for support with the final decision being made by the leadership team. Priority teams would serve for one year. This process had weaknesses that became more apparent with time. Competition among competing interests of scientists within some priority areas led to abrupt changes in program direction from year to year. In time, animosity among priority area participating scientists started to occur. OAP leadership had hoped that interactions would lead to inter-institutional teams, and in some areas just the opposite occurred.

In 2008, the senior author of this article (Dr. Brauer) was selected as OAP Manager. Dr. Brauer had for the prior 10 years managed two large outgoing research efforts as the RL of the ARS-Booneville, AR location so he had substantial experience working with university bureaucracies and scientists. A priority after the hiring of the OAP Manager in 2008 was to change the mechanism by which projects were selected for support. The Leadership Team determined an approximate funding level for each of the seven priority areas. An evaluation matrix for proposed activities was developed and approved by the Leadership Team (Fig. 3). Each research plan was reviewed by at least four peers: a leadership team member, a representative from the OAP manager, a representative from the RL in Lubbock, and one to two other scientists that may or may not have been participants in the OAP. An average score was determined from the peer reviews and the plans were ranked according to average score within the priority area. The ranking versus funding levels were initially reviewed by the OAP Manager and the RL-Lubbock, and these two individuals adjusted the plans recommended for support by slight changes in the funding per priority area. These recommendations were then presented to the entire leadership who by consensus determined final support. This selection process removed some of the conflict among participating scientists within a priority area.

From FY2003 to FY2013, funding by priority area varied substantially (Fig. 4). Funding for projects in the priority area related to water use by CAFOs and agricultural industries was the least, reaching approximately 4% of the funds provided by priority area. Projects supporting objectives related to precipitation and irrigation water use priority areas received the greatest portion of funding, exceeding 25% of the total funds. The assignment of funds to priority areas prior to the review of plans created a situation in which the possibility for support was greater in some priority areas than others. During the time frame that the

OAP Preplan Rating Sheet

Ogallala Aquifer

Criterion 1: Technical Impact Potential **Weight: [30%]**

- Does the Preplan address issue(s) related to a high priority objective/sub-objective of the OAP list of priorities and/or ARS NP211 Action Plan Areas that relate to OAP? [[http://www.ars.usda.gov/research/programs/programs.htm?NP_CODE=211]
- Within an identified high priority OAP objective/sub-objective, does the Preplan address a critically needed information or technology gap?
- Where appropriate, does the Preplan involve a multi-location, multi-institutional team across an important Ogallala Aquifer region? Projects that involve more than one of the OAP institutions are encouraged.
- Is the Preplan innovative and/or creative?

Criterion 2: Technical Approach **Weight: [30%]**

- Degree to which the proposed Preplan is clearly stated and organized as an indicator of the potential to complete planned research adequately for the stated objectives
- Adequacy of the identified research individual (or team) to complete stated objectives
- Adequacy of existing facilities, resources to complete the stated objectives; does the proposed research leverage existing resources (physical and human)?
- Likelihood of obtaining identified deliverables
- Is the request amount appropriate for the proposed work?

Criterion 3: Economic and Technical Assessment* **Weight: [20%]**

- Is the economic assessment plan appropriate or needed at this time?
- Does the economic assessment plan use novel or advanced techniques?

Criterion 4: Technology Transfer Plan* **Weight: [20%]**

- Has the team developed a plan for dissemination of developed knowledge and/or technology to end users that is appropriate for the research being conducted?
- Are the appropriate customers and stakeholders addresses in the technology transfer plan?
- Can the technology be used effectively to train or educate the public, stakeholders and/or producers?

Figure 3. Preplan evaluation matrix (2010).

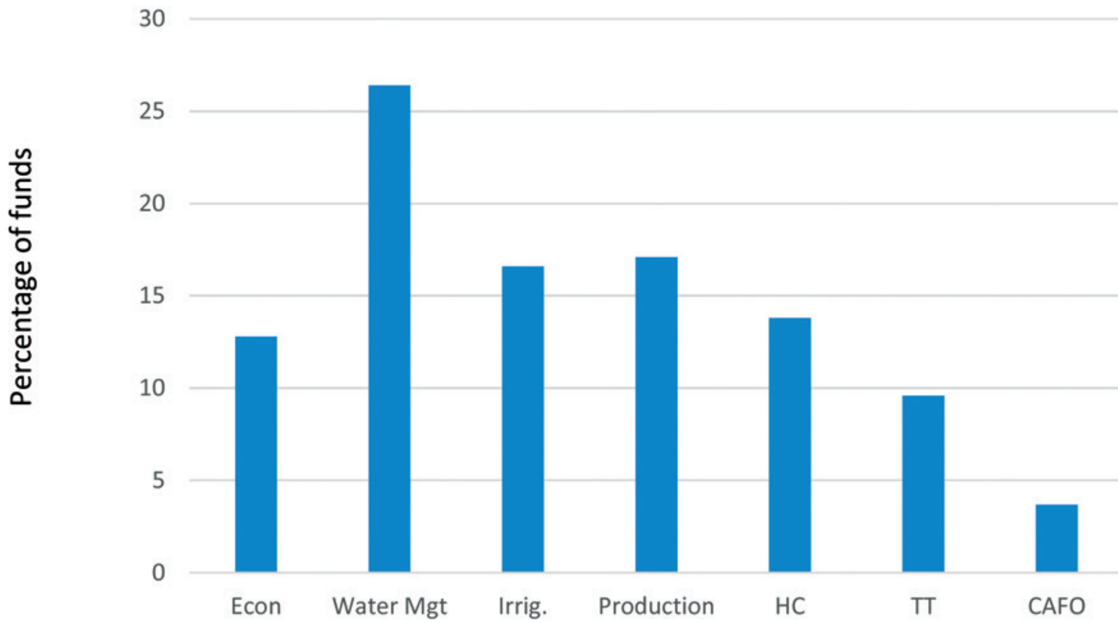

Figure 4. Percentage of the total OAP funding among the seven prioirty areas from FY2003 to FY2013. Priority areas are abbreviated: 1) Econ: Economic Assessment and Impact; 2) Water Mgt: Irrigation and Preciptation Management; 3) Irrig.: Irrigation Systems and Technologies; 4) Production: Integrated Crop and Livestock Systems; 5) HC: Hydrology and Climatology; 6) TT: Technology Transfer; and 7) CAFO: Water use by CAFO and Agricultural Industries.

OAP had seven priority areas, the probability for support was about one out of three. However, there was great disparity between the priority areas. For instance, no suitable plan was submitted in the priority area for evaluating water use by CAFOs and agricultural processing industries and therefore the probability for support was zero. Plans in the economic assessment and impact priority area tend to have a higher success rate than in any of the other six areas.

From FY2005 to FY2007, substantial increases in funds for ARS' portion of the OAP was provided by Congress but ARS was unable to fully utilize these funds because personnel needed to be hired. ARS members of the Leadership Team offered to make $2,000,000 available over three years for two large multi-location and multidisciplinary efforts and the overall Leadership agreed to support two such projects: 1) integration of hydrological and economic data and models to assess economic impacts of water policy scenarios; and 2) investigations into the plant physiological basis for drought tolerance in four major crops of the Southern High Plains, cotton, wheat, sorghum, and corn. The economic-hydrological team made substantial progress on the development of an economic-hydrological model to predict changes in crop acreages and returns at the county level, though a model to predict such trends at a farm level was not realized. The plant physiology project produced numerous journal publications, but no unifying theories on the underlying mechanism of drought tolerance were put forth.

The accomplishments of both large projects were limited, due to a lack of leadership. The OAP Leadership Team expected someone from within each of the large project's team to emerge as the leader, but this did not occur. The Leadership Team did not provide incentives and support for a project member to encourage coordination and leadership roles. As a reminder, these large projects occurred prior to the hiring of an ARS program leader. If there had been an OAP manager, that individual could have provided that coordination and leadership for these large projects. Team members were chosen in large part by the Leadership Team to ensure that the funds were distributed among the different participating entities, rather than considering team members' expertise and probably more important, team members' ability to act synergistically.

During this period of time, the OAP had a formal annual and final project reporting process. A progress report was due 18 months after funding was provided and a final report was due 30 months after funding was provided. Participating scientists were encouraged several times a year to report journal articles that had resulted from OAP funding. These articles were included in the project's annual report.

Current Program Objectives and Management

In large part due to the leadership of the ARS' Southern Plains Area Director, Dr. Dan Upchurch, the objectives of the OAP changed in FY2014. Dr. Upchurch's primary concern was that the objectives of the OAP be related to measureable outcomes. Another concern he had was that after 10 years, a level of complacency had developed among participating scientists. Dr. Upchurch invited the OAP Leadership Team to College Station, Texas in November 2013 and charged the group with defining a handful of objectives to replace the seven priority areas. Four objectives emerged from this meeting: 1) Develop and evaluate water management strategies and technologies that could reduce water withdrawals for irrigation by 20% in 2020 compared to 2012, while maintaining and/or enhancing the economic viability of the agriculture industry and the vitality of the Southern Ogallala Aquifer Region; 2) Develop and evaluate management strategies and technologies that would increase the productivity and profitability of dryland cropping systems; 3) Improve the understanding of hydrological and climatic factors that affect water use and economic profitability, and provide estimates of the climatic, hydrologic, cropping, and profitability conditions that are likely to occur on the Southern High Plains over the next 50 years; and 4) Determine the impacts of alternative water withdrawal/use policies on the economic viability of the agriculture industry and the vitality of the Southern Ogallala Aquifer Region. Starting in FY2014, submitted plans were evaluated by a peer review process similar to that described earlier, but with regard to the above four objectives. A fifth objective was added in FY2017: 5) Develop best management practices for alternative dryland and high value irrigated crops that can sustain farm level income and profitability as pumping from the Ogallala Aquifer declines. By and large, stand-alone technology transfer activities were not encouraged under these objectives but PrePlans with strong technology transfer and economic assessment aspects were more likely to be supported because of the evaluation matrix. In 2016, a stand-alone technology transfer activity related to 40 years of sprinkler irrigation research on the High Plains was selected for support. The evaluation process and matrix remained as before. However, no target funding levels were designated for the objectives.

Collaborative activities are facilitated by an annual workshop in which program scientists participate. The annual workshop is also a forum in which research priorities from stakeholder groups are presented. Attendance varies from 80 to 150 participating scientists, graduate students, and stakeholders. The annual workshop is held at different venues with typical rotations involving Lubbock and Amarillo, TX and Garden City, KS; however, the workshop has been held in Manhattan, KS as well.

In 2014, the manager of the OAP assumed additional responsibilities as the Research Leader of the Soil and Water Management Research Unit. Then later, in 2016, the manager also assumed responsibilities of Acting Laboratory Director for the Center for Public Research and Leadership (CPRL). These increased duties necessitated changes on the workload for the OAP manager duties. Scientists were provided the option of making an oral or poster presentation at the annual workshop rather than submitting a report. As such, since 2014, a poster session has become a standard feature of the program's annual workshop. These changes were implemented in part to reduce the work load of the OAP Manager after he became RL of the Soil-Water unit.

Awards and Outcomes

The OAP has been recognized several times for its accomplishments related to production agriculture, irrigation technologies, and water conservation. These awards document the outcomes of the OAP to date and therefore are worthy of examination.

Irrigation Symposium (2009)

Every ten years the Irrigation Association sponsors at its national annual meeting a symposium summarizing the recent advances in irrigation research. In 2009, the Fifth National Decennial Irrigation Symposium features advances arising from the support by the OAP. The symposium featured 18 presentations from OAP researchers. The presentations were the basis of proceeding articles that were published in 2010 in the Transactions of the American Society of Agricultural and Biological Engineers.

Exemplary Example of Cooperative Agricultural Related Research Program (2011)

In the fall of 2010, there was a call for nominations from a consortium of agricultural related organizations including Farm Foundation, Charles Valentine Riley Memorial Foundation, and others, for Exemplary Examples of Cooperative Research and Development Programs to be presented at the Agriculture, Food, Nutrition, and Natural Resources R&D Round Table in the spring of 2011. There were over 50 nominations and eight were selected. The OAP was the only group selected that conducted research related to production agriculture.

The nomination material indicated that a major accomplishment of the OAP from 2003 to 2010 was its impact on water conservation, that is, management practices to reduce withdrawals from the aquifer and thus sustain economic benefits derived from its use in Texas. The Texas Legislature, through the Texas Water Development Board, has divided the state into 16 water planning regions, two of which are located above the Ogallala Aquifer. These water planning regions must create 50-year water plans that are updated every five years. In Region A (Panhandle portion of Texas), the 2011 water plan (Panhandle Water Planning Group 2011) indicates that the demand for water will exceed the supply in most counties in which irrigation is occurring for most of the next 50 years (2010-2060) if the status quo is maintained. However, the region's 2011 water plan indicates that this supply deficit can be turned into modest supply surplus by the adoption of OAP research results in the areas of best cropping practices, improved irrigation scheduling to better match crop needs with water applications, and continued adoption of efficient irrigation systems. Research activities of the OAP produced over 20 peer reviewed journal articles annually since 2005. In 2010, the OAP maintained a public web site: http://www.ogallala.ars.usda.gov/. The web site provided access to research projects' final reports, annual accomplishment statements, news items related to the Ogallala Aquifer and the OAP, and calendar of events. However, due to internet security issues the site was taken down in 2014. A new site that is hosted by Texas A&M AgriLife's Texas Water Resource Institute went online in June 2017 (http://ogallala.tamu.edu/). Archived material from the original site (2010-2012) is available at: http://web.archive.org/web/20130217193538/http://www.ogallala.ars.usda.gov/index.php.

The eight selected groups made presentations at the Association for the Advancement of American Science (AAAS). The presentations were distributed over the internet to over 100 locations.

Blue Legacy Award for Agriculture (2012)

The Water Conservation Advisory Council of Texas presents annually the Blue Legacy Award(s) for Agriculture to individuals and groups that have promoted water conservation in Texas. In 2012, the OAP was presented with one of the 2012's Blue Legacy Awards.

The nomination materials included the following accomplishments. Since the 2000s, the 16 water planning regions in Texas have been charged with the development of a water plan that determined water supply shortages and means to overcome those shortages. The 2011 Region A (Texas Panhandle) Water Plan identified at least five counties in which the demand for irrigation water from the Ogallala Aquifer will exceed supply under current practices. This difference between irrigation demand and water supply is expected to grow between 2010 and 2040, and then decrease between 2040 and 2060 due to the conversion of irrigated acres to dryland farming. Under such a scenario, the region is expected to lose nearly $1 billion in annual agricultural sales.

The regional water planners examined the impact of implementation of water conservation practices based on OAP research: 1) Continued adoption of water efficient irrigation systems, like low pressure center pivot systems, and subsurface drip; 2) Irrigation scheduling based on crop needs, using real time sensors that detect crop water stress, and/or the integration of weather data with patterns of crop water use; and 3) Use of crop species and varieties that have lower water requirements, including support for the development of drought and heat tolerant germplasm for sorghum, corn, peanuts, and wheat. Adoption of these water conservation practices is projected to reduce the difference in the water demand for irrigation and water supply to the extent that supply will exceed demand from 2050 to 2060. Such conservation efforts are expected to maintain the $4 billion agricultural economy of the Texas Panhandle.

Water conservation practices currently being researched that will facilitate future water savings include: 1) Development of technology and management practices for the use of variable rate irrigation controls and supervisory control and data acquisition (SCADA) to improve the efficiency of irrigation applications; 2) Management practices that better match water needs to cropping practices that integrate whole farm operations, both in terms of time (multiple years) and different fields and/or irrigation systems; and 3) Development of soil moisture sensors that can provide real time, accurate information on total soil water availability.

Although water use by CAFOs and animal processing facilities represent a small part of the water use in the Texas High Plains, high water use by these entities can significantly affect their profitability. Research conducted by OAP participating scientists has provided sound estimates of water use by these industries and means of which water can be used more efficiently (Guerrero and Amosson 2013a; 2013b). This information is needed by water policy makers to understand their contribution to the regional economy.

The OAP has supported educational activities to facilitate the transfer of information to end users. These activities include but are not limited to: 1) Development and support for hands-on training sessions and/or self-help on-line resources available through Texas A&M AgriLife or Kansas State University; 2) Development of software that helps farmers and irrigators allocate their water resources to different crops and fields to optimize water use and returns; 3) Hosting an annual workshop in which participating scientists and stakeholders exchange information; and 4) Support for farm days and demonstration projects including support for the scientists and extension agents who were involved in the North Plains Groundwater Conservation District 200 bushels with 12 inches challenge, recognized in 2011 with a Blue Legacy Award in Agriculture.

The activities of the OAP have been instrumental in the development of mass media stories on water conservation and the importance of the Ogallala Aquifer to world food production in such outlets as CNN and National Public Radio's Marketplace. Participants in the OAP tend to be leaders in their local communities with respect to water conservation. Many of the program participants in the Amarillo area have been involved in the development of Region A water plans.

The OAP is a regional project that has significant efforts directed towards water conservation in western Kansas. The OAP had a significant impact on water policies in western Kansas over the last two years. In 2011, Governor Brownback of Kansas spearheaded an effort to change water policies that will help sustain the economic activity derived from the Ogallala Aquifer. A Governor's Economic Summit for the Future of the Ogallala Aquifer was held in July 2011, and led to the creation of the Ogallala Aquifer Advisory Committee (OAAC). The OAAC's recommendations for changes in state water policies were largely based on investigations supported by the OAP. New state legislation passed during the spring of 2012 was described above.

Honor Award for Excellence from the Secretary of Agriculture (2013)

In 2013, the OAP received an Honor Award from the U.S. Secretary of Agriculture for its effort "Sustaining rural prosperity on the drought prone Southern High Plains by finding solutions to problems arising from declining water in the Ogallala Aquifer". Outcomes from this project that conserve water and promote agriculture include:

1) Irrigation scheduling using evapotranspiration demand has reduced water application by 15% over the past 10 years, saving farmers approximately $200 million in production costs; 2) Advances in the design and management of subsurface drip irrigation has led to the doubling of the acres using this water conserving technology since 2003; 3) New irrigation automation systems could benefit 6 million acres by reducing labor costs by $7 per acre while maintaining crop yields; 4) Development of drought and heat resistant crop varieties has been advanced for corn, cotton, sorghum, wheat, and peanuts; 5) Thousands of farmers have been educated in water conservation practices through extension programs and millions have been exposed to the importance of the Ogallala Aquifer to national and world food and fiber supply via public media stories.

The OAP supported water policy changes in Kansas. In 2011, Governor Brownback of Kansas spearheaded an effort to change water policies that will help sustain the economic activity derived from the Ogallala Aquifer. State legislation passed during the spring of 2012 included: 1) repeal of “use it or lose it” for groundwater rights; 2) creation of Local Enhancement Management Plans; 3) creation of water banks for market-based reallocation of water use and conservation, and repeal of the 10% set aside for deposited water; and 4) amendments to the multi-year flex accounts to provide irrigators with flexibility while eliminating the 10% conservation penalty. Research from the OAP indicated that enactment of these four initiatives will not increase groundwater withdrawals while helping to sustain farm and regional economies. Additional research by the OAP provides the tools and knowledge that irrigators and farmers need to take full advantage of these changes in state and local water policies.

The accomplishments of the OAP directly support several of the USDA’s priorities. For example, the OAP supports the USDA Strategic Goal 1: Assist rural communities to create prosperity so they are self-sustaining, repopulating, and economically thriving (USDA 2014). A conservative estimate of the value of agricultural production in western Texas and Kansas is $10 billion in 2012. The multiplier effect of irrigated crop production to regional economy is greater than that of dryland farming because irrigated agriculture requires more inputs and services. Therefore, agricultural production in this region may have an economic impact exceeding $20 billion. A significant portion of this agricultural economy is at risk for declining water availability from the Ogallala Aquifer. Localized areas where irrigated agriculture has declined sharply because of severe depletion of the Ogallala Aquifer have already experienced economic decreases and depopulation, for examples, Happy, TX and Greely County, KS. Widespread occurrence of decreased economic activity and depopulation could occur without the accomplishments of the OAP creating information and technologies to increase water conservation and sustain economic activity generated by the water withdrawn from the aquifer.

The OAP is also supporting other USDA goals, such as Pillar 2 of Objective 1.1, facilitating sustainable renewable energy development (USDA 2014). Research results from the program are leading to the development of management practices that enhance both the dryland and irrigated production of feedstock for biofuel production. Economic analyses that support the Ogallala Aquifer Program indicate that per unit of water pumped from the aquifer a biofuel plant supports over 10 times the number of jobs as irrigated crop production (Guerrero et al. 2011). Additionally, the OAP is helping the USDA meet Performance Measure 1.3.6 (Increasing the number of students enrolled in agriculture related degrees by 20%) by training an average of 18 undergraduates, 22 master degree students, and 10 Ph.D. students between FY2010 and FY2013. Increasing the number of people graduating with professional degrees related to agriculture and natural resources has been a long standing goal of the USDA (USDA-REE 2012).

A unique outcome of OAP activities has been the forming of teams that probably would not have developed independently. An Economic Impact and Assessment Team has emerged under the program’s umbrella. This team, with at least one representative from each of the four universities, has become prolific in impactful research output, providing insights into the possible outcomes of different water conservation strategies. A team from Kansas State University and Texas A&M University hosted a multi-day multi-location outreach effort summarizing 20 years of research regarding the installation and management of subsurface drip irrigation. A broader team has formed to celebrate 40 years of sprinkler irrigation on the High Plains with several technology transfer events in 2018. The usefulness of decision support tools that Kanas State University was developing for Kansas irrigators was extended by the adaptation for use by Texas irrigators. During this process the team developed a means by which these irrigation tools could efficiently and quickly be adapted to anywhere in the world.

Conclusion

Since 2013, the OAP has continued to be productive and serve the needs of the Southern Ogallala Aquifer Region. In 2016, leaders in the OAP in conjunction with prestigious water conservation researchers from Colorado State University, Oklahoma State University, New Mexico State University, and University of Nebraska were granted an USDA-NIFA CAP grant to further the understanding of the resiliency of the Ogallala Aquifer in light of climate change and changes in production systems. In 2017, leaders within the OAP and the NIFA CAP grant presented a special symposium within the Universities Council on Water Resources (UCOWR) 2017 Annual Conference on management practices to sustain aquifers that have been decreasing in water availability. This article is drawn from that symposium.

At the time of writing this article (spring 2017), there is uncertainty how the new Trump administration will affect the OAP. President Trump's initial budget for FY2018 had only passing comments regarding ARS. It is hard to believe that continued support for the OAP is not a high priority since the Ogallala Aquifer Region is one of the most productive crop and livestock production areas in the U.S. (Gollehon and Winston 2013). The current hiring freeze and the administration's stated intentions to reduce the federal workforce may affect the OAP. It is unfortunate that restrictions resulting from the administration goal of reducing the federal workforce may create barriers to the USDA's goal related to the development of next generation agricultural related professionals.

Although there are uncertainties arising from a new Presidential administration, there is hope that the future for the OAP is bright. Through continued research and technology transfer activities the OAP has been successful in providing knowledge that will sustain rural economies in the Southern Great Plains as water available for irrigation from the Ogallala Aquifer decreases. In accomplishing this mission, OAP researchers have contributed significantly to the research and technology transfer activities related to irrigation technology and irrigation best management practices. In addition, the OAP addresses knowledge and technology related to subjects other than irrigation, including dryland farming, hydrology, climatology, etc. Research results will facilitate efficient use of the Ogallala Aquifer, increase the sustainability of dryland farming, and provide water use planners and policymakers with valuable knowledge and tools. The outcomes that Congress intended when it provided the initial funding in 2003 are bearing fruit.

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Kansas Trends and Changes in Temperature, Precipitation, Drought, and Frost-Free Days from the 1890s to 2015

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Abstract: Kansas extends 660 km from the moderate elevations and semi-humid conditions of the Lower Missouri Basin to the High Plains lying above the Ogallala Aquifer and along the Rockies' eastern slope. Such characteristics result in significant climate variability across the state, making timely and accurate climate trend and change information valuable for water resources management and crop production. Here we used high-quality daily and monthly climate observations spanning a long-term period of 121 years (1895-2015) to assess trends and changes in air temperature, precipitation, drought, and frost-free days across Kansas. We show that a statewide average warming rate of 0.06°C (0.11°F) per decade was mainly driven by trends in daily minimum temperatures. However, there were no statistically significant trends in precipitation in either western, central, or eastern Kansas. Western Kansas tended toward increasing dryness, but central and eastern Kansas trended wetter as indicated by changes in the Palmer Drought Severity Index (PDSI), a trend that was consistent with a weak wetting signal in eastern Kansas. The length of frost-free season increased by 5.2 days in western, 7.2 days in central, and 12.6 days in eastern Kansas, which reflected more warming in the east and less in the west, especially for changing magnitudes of nighttime temperatures. Such increases of frost-free days, especially in moisture-limited areas (e.g., western Kansas), might increase seasonal evapotranspiration loss, thus exacerbating soil moisture stress and associated management challenges.

Keywords: *climate, water resources, drought, climate change, trends*

Nearly seventy years ago, Snowden Flora, a meteorologist of the U.S. Weather Bureau located in Kansas, published the 'Climate of Kansas' (Flora 1948). This book did an excellent job of documenting the weather and climate conditions for Kansas, based on instrumental observations from the late nineteenth century to the 1940s, and putting them into an accurate historical perspective. Following up this work, a few scientists have published research and educational bulletins and/or books detailing aspects of the climate of Kansas. For example, Bark, in 1963, published a Kansas Agricultural Experiment Station Bulletin on precipitation change in Kansas. Later, Feyerherm and Bark (1964) calculated wet and dry days in Kansas, and in the mid-1990s, Goodin et al. (1995) published the Kansas Climate and Weather Atlas. These publications have not only advanced climate science in Kansas, but more importantly, they successfully helped to assist Kansas stakeholders in climate-informed decision-making. However, these publications are constrained by the use of a limited set of climate stations and/or relatively short periods used for data analysis.

The ability to organize a more comprehensive documentation of Kansas climate now exists. One of the reasons is that climate scientists working on long-term climate data quality and data homogeneity have been making significant progress addressing climate data quality starting from the 1980s (Karl et al. 1986; Karl and Williams 1987; Menne and Williams 2009; Menne et al. 2012). Another reason to provide updated information on Kansas climate trends and changes is that climate change, including detection and attribution, has been vigorously and extensively studied since 1990, the year of the first Intergovernmental Panel on Climate Change (IPCC) Assessment Report in which the challenge of climate change was addressed (IPCC 1990).

This study is designed to foster the growth of climate science information in the areas of long-term climate changes and extreme weather records for Kansas. As the IPCC authors (Field et al. 2012; IPCC 2013) concluded that "it is likely that anthropogenic influences have led to warming of extreme daily minimum and maximum air temperatures at the global scale" and that "there is medium confidence that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale".

While these global scale changes have an influence on the climate of Kansas, other factors help explain the specific conditions across the state. At the local scale, climates are affected by various factors that include topography, elevation, proximity to oceans, water in lakes and rivers, irrigation practices and other land cover changes, and latitude. The borders of Kansas extend 660 km to include the moderate elevations and abundant precipitation conditions (more than 1,000 mm [~40 inches] of annual precipitation) of the Lower Missouri Basin to the drier High Plains lying along the eastern slope of the Rockies (with less than 500 mm [~20 inches] of annual precipitation). The Gulf of Mexico, which extends westward to the 98th meridian, is the source of the vast majority of moisture for precipitation in Kansas. Northward flow of water vapor associated with low-level jets is frequently pushed eastward and this atmospheric moisture flow pattern contributes to three quite distinct precipitation climate zones of Kansas: a semiarid western third, an intermediate central third, and a semi-humid eastern third (Flora 1948).

Given the mid-latitude and mid-continental location of Kansas, pronounced thermal and hydrologic seasonality characterizes the climate of Kansas. The primary objective of this study is to document and analyze trends and changes in air temperature, precipitation, drought, and frost-free days that have occurred from 1895 to 2015, as well as the related extreme climate records for the 1891-2015 period across Kansas.

Data and Methods

Daily climate data were obtained from the Global Historical Climatology Network (GHCNd). The U.S. component of GHCNd is an integrated version of NCEI's (National Centers for Environmental Information) daily surface observations, including the U.S. Cooperative Observer Network, the Automated Surface Observing System (ASOS), and other observing systems, and represents the most complete historical record of daily data for the United States. Thirty long-term climate stations (Fig. 1) were selected across Kansas for January 1, 1891 to December 31, 2015 based on data availability and station continuity. This daily dataset is part of the U.S. Historical Climatology Network (USHCN) program (Menne et al. 2012). This dataset was subjected to high-quality control (Alexander et al. 2006), but there were still erroneous observations for some Kansas stations. We first identified erroneous temperatures by using the fourth standard deviation as a threshold and then visually assessed suspected records by a spatial correlation method (Alexander et al. 2006). For daily precipitation observations, we only used them to assess the climate extreme records (when analyzing monthly and annual precipitation, we used the monthly dataset) for Kansas.

The U.S. Historical Climatology Network (USHCN, version 2.5) consists of 31 high-quality stations in Kansas and the data quality of monthly average temperatures has been rigorously examined (Menne and Williams 2009; Lawrimore et al. 2011; Menne et al. 2012) (Fig. 1). These 31 USHCN stations have long been commonly selected for use in evaluating climate changes on the global, regional, and state scales and these temperatures are considered a high-quality reference base when evaluating climate change from 1895 to 2015.

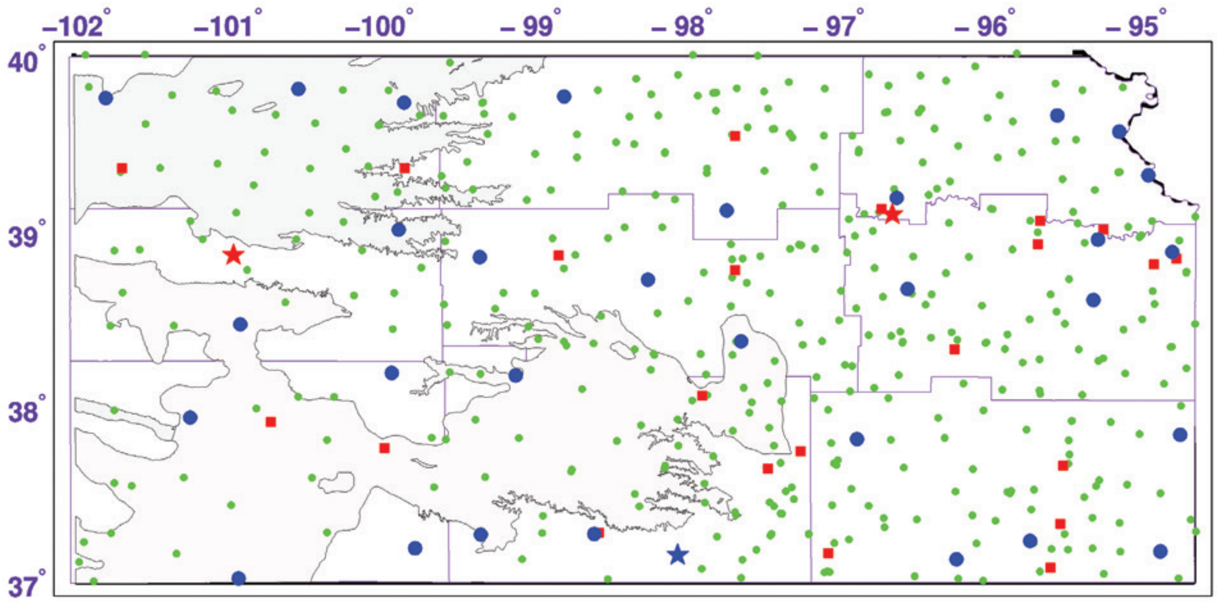

Figure 1. 433 total active daily climate observing stations (green dots) which include 30 long-term (over 1860s to current) high quality daily stations (blue dots) and 31 long-term monthly stations (blue dots plus one blue star) in Kansas selected by the Global Historical Climatology Network (GHCN). Kansas also has 22 federal ASOS stations (red squares) with data from the 1970s to current, and two U.S. Climate Reference Network (USCRN) stations (red stars), from 2002 to current. Aquifers in western Kansas and the nine crop reporting districts are shown. Each third of Kansas contains at least nine high-quality stations analyzed in this report. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

In both daily and monthly datasets that we used in this study, all missing data were retained without any filling or replacement by estimation. Monthly anomalies for maximum, minimum, and average temperatures were departures from a base period of 1981 to 2010 (WMO 1989; WMO 2009). The time series for the state of Kansas was aggregated using an equally weighted station average from each station when the observation was available. It should be noted that the monthly climate data were different from the daily climate data in that there were extensive and high-quality data homogeneity techniques employed in generating the monthly datasets but these procedures were not used for the daily dataset (Menne et al. 2012).

For derived climate variables in this study, the PDSI was selected, an index originally developed and calibrated using western Kansas climate in 1965 (Palmer 1965). The PDSI was calculated from the monthly temperature, monthly precipitation, and Kansas' available water capacity (Guttman 1991). The second climate variable we selected is the frost date, which is defined in this paper as a day with the daily minimum temperature below freezing (0°C). The length of the frost-free season (frost-free days) is defined as the difference between the last-spring freeze and the first-fall freeze dates (Easterling 2002).

To robustly examine the trends, the adjusted standard error and adjusted degree of freedom methods were selected for assessing the statistical significance of temperature trends at 95% confidence levels (von Storch and Zwiers 1999; Santer et al. 2000; Karl et al. 2006; Lin et al. 2016). This approach is a modification of ordinary least squares linear regression, substituting the effective sample size in a regression time series to account for the effect of temporal autocorrelation in the time series or its residual series. The extent of sample number reduction implemented in our linear trend analysis depends upon the strength of the autocorrelation. A strong autocorrelation means that individual values in the sampling series are far from being independent so that the effective number of independent values must be much smaller than the sample size. A trend in a time series significantly different from zero is tested by computing the ratio of the estimated trend and its adjusted standard error, a stricter test than using standard *p*-values. Note that the 95% confidence intervals used in this paper are adjusted by inverting the Student's *t*-distribution to obtain effective sample size and using the critical value $1-\alpha/2 = 0.975$ (two-tailed) (Lin et al. 2016).

Results

Temperatures

Over the last decade, temperatures have been among the warmest on record for Kansas, with the only exception being the extreme heat of 1930s "Dust Bowl" era (Figs. 2a and 2b). Statewide annual average temperature varied from a low of 11.3°C (52°F) in 1912 to a high of 14.9°C (59°F) in 2012. Such a swing, 3.6°C (6.5°F), documents an aspect of temperature variability that is one of the reasons that Kansas' agricultural economy is vulnerable to climate change and climate variability. One pronounced result from observations over the last 121 years was the warming of the minimum temperature (nighttime temperatures) much greater than that of maximum temperatures (Figs. 2a and 2b). Maximum temperatures do not have statistically significant trends over the last 121 years but minimum temperatures show a significant warming rate of 0.078 ± 0.03°C per decade (0.14°F per decade). Kansas' average temperature increase, 0.059 ± 0.03°C per decade (0.11°F per decade), was mainly driven by the rise in minimum temperatures (Fig. 2).

When examining seasonal temperature trends, the results indicate that none of four seasons have any statistically significant trend (Fig. 3) except for the winter season, showing significant warming using a 90% confident level (Fig. 3d). In addition, it is clear that this warming trend of winter temperatures was accompanied with larger inter-season variations compared to spring, summer, and fall seasons (Fig. 3d). These results suggest that temperature change impacts on winter wheat are expected to be more

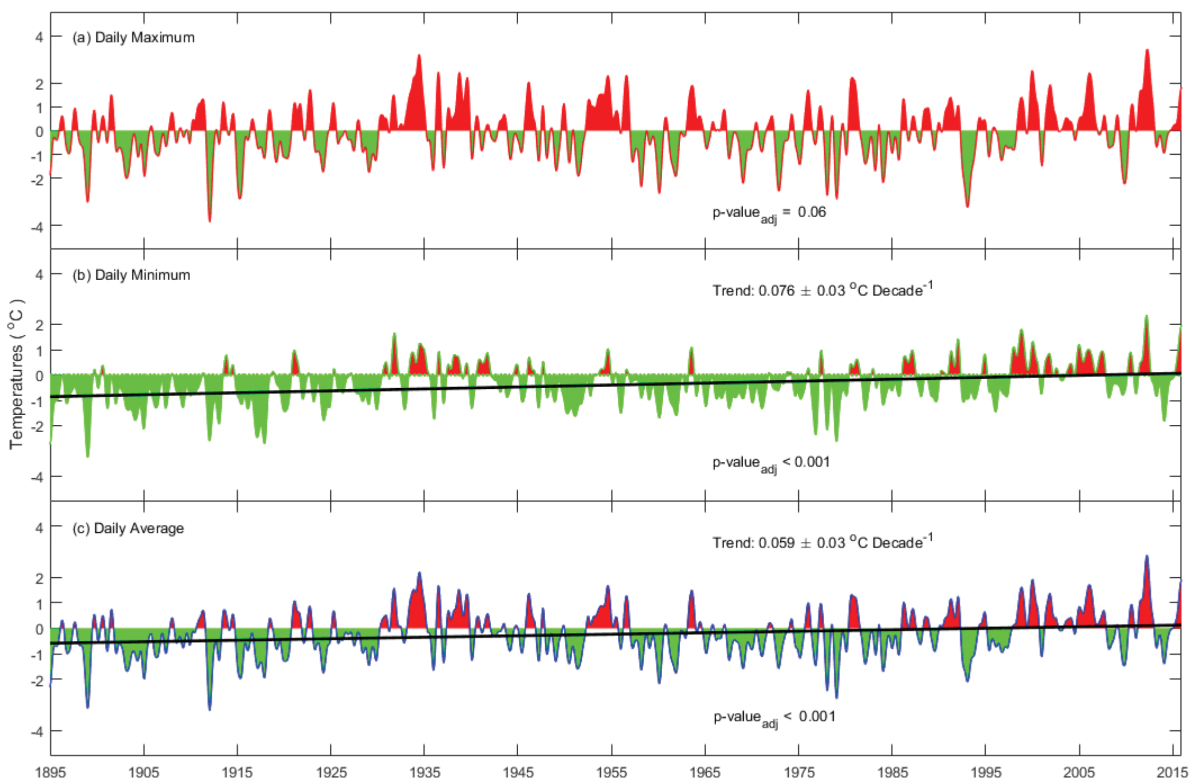

Figure 2. Kansas monthly temperature anomaly time series over 1895 to 2015: (a) daily maximum temperature; (b) daily minimum temperature; and (c) daily average temperature. The base period used is 1981 to 2010 and a 13-point Gaussian filter was used to smooth the data (red line for daily maximum, green line for daily minimum, and blue line for daily average temperatures). When trends (black lines) are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

important than that on other major crops in Kansas (Zhang et al. 2015; Zhang and Lin 2016). It should be noted that this century-scale increase in temperature documented with the analysis of data from stations in Kansas is comparable with the 0.6 to 1.0°C (1.1 to 1.8°F) increases observed across the United States (Karl et al. 2006). Notice that when minimum temperature data are analyzed on a seasonal basis, the data indicate an increase in all four seasons, with the steepest slope in spring (not shown).

Precipitation

Precipitation in Kansas is highly variable from year to year and across the state, with the statewide annual average exhibiting a low of 439 mm (17 inches) in 1956 to a high of 1,110 mm (44 inches) in 1951 (Fig. 4 and Table 1). For the western third, central third, and the eastern third of Kansas, long-term (1895-2015) mean annual precipitation totals were 531 mm (21 inches), 660 mm (26 inches), and 945 mm (37 inches), respectively (Fig. 4). These long-term statistics are slightly larger than those presented by Flora (1948): 474 mm (19 inches) for western, 658 mm (26 inches) for central, and 878 mm (35 inches) for eastern Kansas. Over the last two decades, annual precipitation amounts have increased, but due to large inter-annual (year-to-year) variability the long-term annual precipitation does not show any statistically significant increase or decrease (Fig. 4) at the 95% confidence level for 1895 to 2015. It was clear that if one considers the 90% confidence level, both central and eastern Kansas did present a weak increasing trend (7.08 ± 7.0 mm per decade (0.3 inches per decade) for central and 8.80 ± 9.1 mm per decade (0.4 inches per decade) for eastern, at 95% confidence level) (Fig. 4).

For the state as a whole, the precipitation is 218 mm (9 inches) during spring (March-April-May), 279 mm (11 inches) in summer (June-July-August), 169 mm (7 inches) in fall (September-October-November), and 70 mm (3

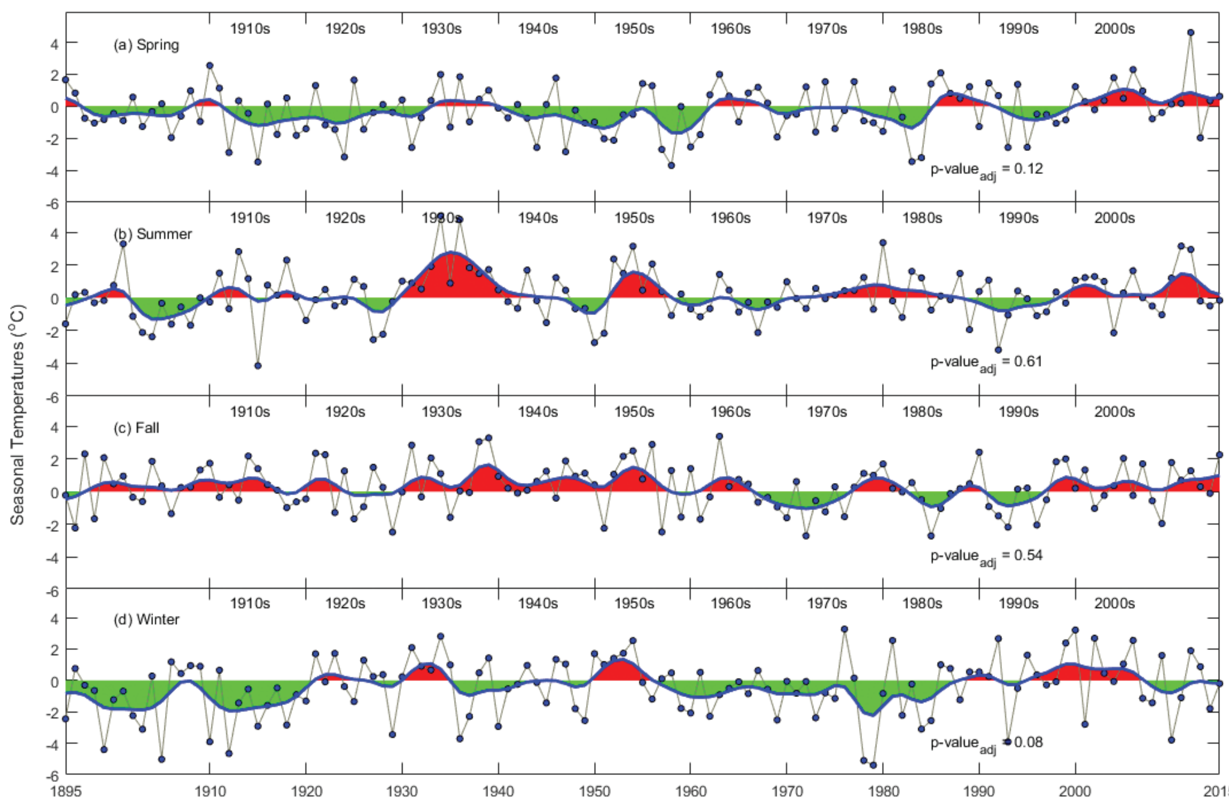

Figure 3. Kansas seasonal temperature anomaly time series over 1895 to 2015: (a) Spring; (b) Summer; (c) Fall; and (d) Winter. The base period used is 1981 to 2010 and a 13-point Gaussian filter was used to smooth the data (blue lines). When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

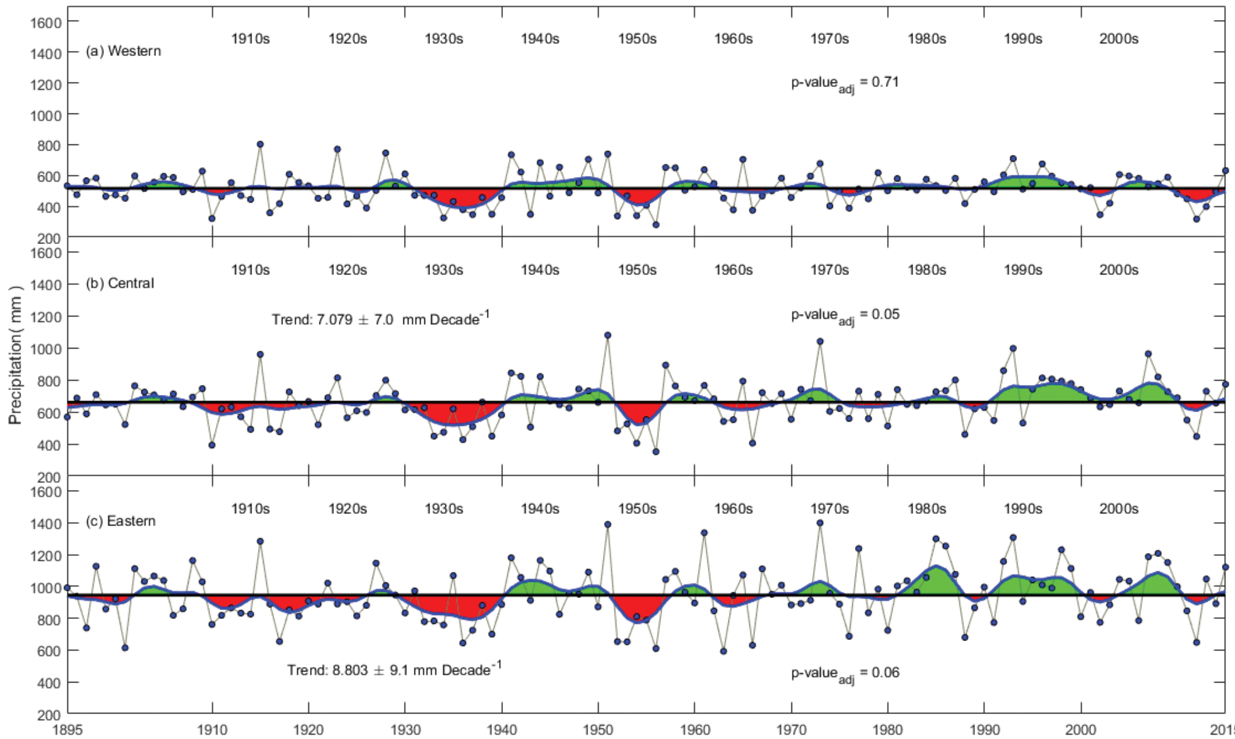

Figure 4. Kansas annual precipitation time series over 1895 to 2015: (a) Western; (b) Central; and (c) Eastern Kansas precipitation variations. The black lines are period-of-observation mean over 1895 to 2015 (inclusive). A 9-point moving average was used as a smoother (blue lines). When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

inches) in winter (December-January-February) seasons (Fig. 5). Winter season precipitation has a comparatively small inter-annual variation. There were no statistically significant trends in seasonal precipitation amount at the 95% confidence level. For the whole U.S., extreme precipitation events are increasing (Karl et al. 2006) and data for Kansas documents a statewide increase in the magnitude of extreme rainfall events, with greater increases in the east (Rahmani et al. 2016). At the 90% confidence level of statistical significance, seasonally, only spring precipitation showed an upward trend.

Drought

Droughts are one of the most devastating natural disasters. Over the course of the time period studied here, the water resources and agricultural economy of Kansas have been considerably effected by drought events. The 1930s drought is often considered the worst drought on record in Kansas (Fig. 6a). This was the driest series of years since instrumental observations began starting in the late 1800s. Sporadic weather observations in the mid-1800s have helped document droughts during that settlement period.

By going over more than 1,000 years of tree-ring data (Cook et al. 2004), it becomes noticeable that the droughts in 1930s were not the worst in history in terms of either drought duration (consecutive years of drought) or drought intensity (the magnitude of drought index) in Kansas. Multiple-year droughts have often occurred in Kansas. The state as a whole has not experienced more frequent or more extreme droughts in recent years compared to either the last 1,000 years (Cook et al. 2004) or the most recent 121-year period (Fig. 6). When the data were subdivided by dividing the most recent 121-year period into two periods (1895 to 1955 and 1956 to 2015) for each of the three regions of Kansas, only western Kansas was dryer on average during the most recent 60-year period when compared to data from 1895 to 1955 (Fig. 7). Both central and eastern Kansas showed

Table 1. Kansas top ten hottest and coldest years (top panel), and driest and wettest years (bottom panel) from 1895 to 2015.

Rank	Hottest Year	°C (°F)	Rank	Coldest Year	°C (°F)
1	2012	14.9 (58.9)	1	1912	11.3 (52.3)
2	1934	14.5 (58.1)	2	1951	11.4 (52.5)
3	1954	14.3 (57.7)	3	1993	11.4 (52.6)
4	2006	14.2 (57.6)	4	1924	11.4 (52.6)
5	1938	14.2 (57.5)	5	1917	11.5 (52.7)
6	1939	14.1 (57.4)	6	1979	11.6 (52.8)
7	1946	14.1 (57.4)	7	1903	11.6 (52.9)
8	1933	14.1 (57.3)	8	1895	11.6 (52.9)
9	1931	13.9 (57.1)	9	1929	11.6 (52.9)
10	1921	13.9 (57.1)	10	1985	11.7 (53.0)

Rank	Driest Year	mm (inches)	Rank	Wettest Year	mm (inches)
1	1956	439 (17.3)	1	1951	1110 (43.7)
2	1966	490 (19.3)	2	1973	1085 (42.7)
3	2012	493 (19.4)	3	1915	1049 (41.3)
4	1936	503 (19.8)	4	1993	1044 (41.1)
5	1952	511 (20.1)	5	1961	968 (38.1)
6	1939	526 (20.7)	6	1941	953 (37.5)
7	1910	526 (20.7)	7	2007	930 (36.6)
8	1917	533 (21.0)	8	1944	925 (36.4)
9	1963	536 (21.1)	9	1985	912 (35.9)
10	1988	541 (21.3)	10	1992	909 (35.8)

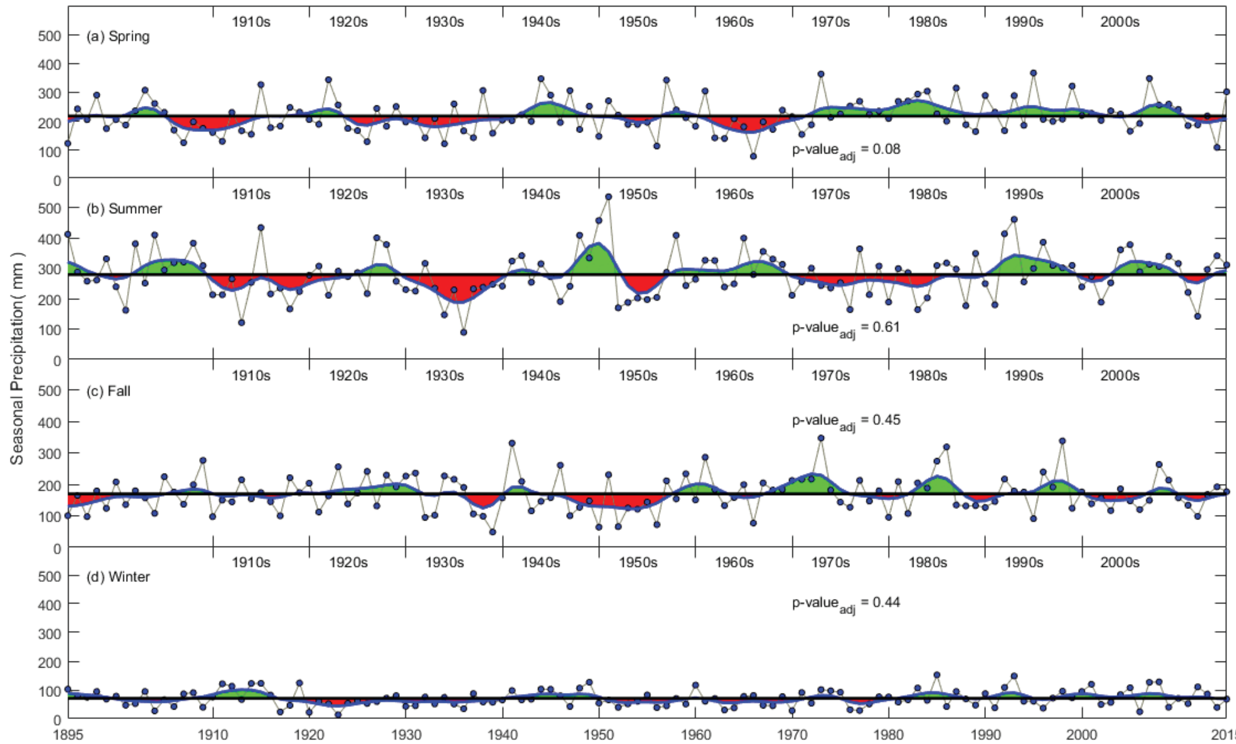

Figure 5. Kansas seasonal precipitation time series over 1895 to 2015: (a) Spring; (b) Summer; (c) Fall; and (d) Winter seasons. The black lines are period-of-observation mean over 1895 to 2015 (inclusive). A 9-point moving average was used as a smoother (blue lines). When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

wetter tendencies in the most recent 60-year period. Recent wetter conditions are challenging summer row crop establishment and final harvest. The drought change information observable in Figure 7 is consistent with precipitation trends for Kansas (Fig. 4).

Frost-free Days

The number of days that the minimum daily temperature falls below freezing is an important indicator for crop production, water management, and ecosystems in Kansas (Lin et al. 2014). Length of the frost-free season and changes in the length of that season have a direct implication for crop production in Kansas. The distinct patterns of first and last frost dates across Kansas result in the shortest growing season occurring in western Kansas (170 days) and longer average growing seasons occurring in central Kansas (182 days) and eastern Kansas (189 days) (Fig. 8). These long-term averages for Kansas are changing (Lin et al. 2014). The frost-free season length in all regions of Kansas exhibits a statistically significant increase from 1901 to 2014 at a rate of 0.99 ± 0.79 days per decade in western Kansas, 0.94 ± 0.90 days per decade in central Kansas, and 1.47 ± 0.74 days per decade in eastern Kansas (Fig. 8). A longer frost-free growing season could give Kansas producers an opportunity to explore cropping alternatives. This longer season could increase yields if other biotic (insects, diseases) and abiotic (heat, drought) stresses do not limit crop growth and development.

Top Ten Hottest, Coldest, Driest, and Wettest Years

Table 1 provides the top ten hottest, coldest, driest, and wettest years, respectively, based on the daily climate data. The hottest year was 2012 and coldest year was 1912. Five of the ten hottest years occurred during the 1930s. Both the driest and wettest years occurred in the 1950s. Perhaps surprisingly, only two of the driest years were during the Dust Bowl decades of the 1930s (Table 1). The temperature

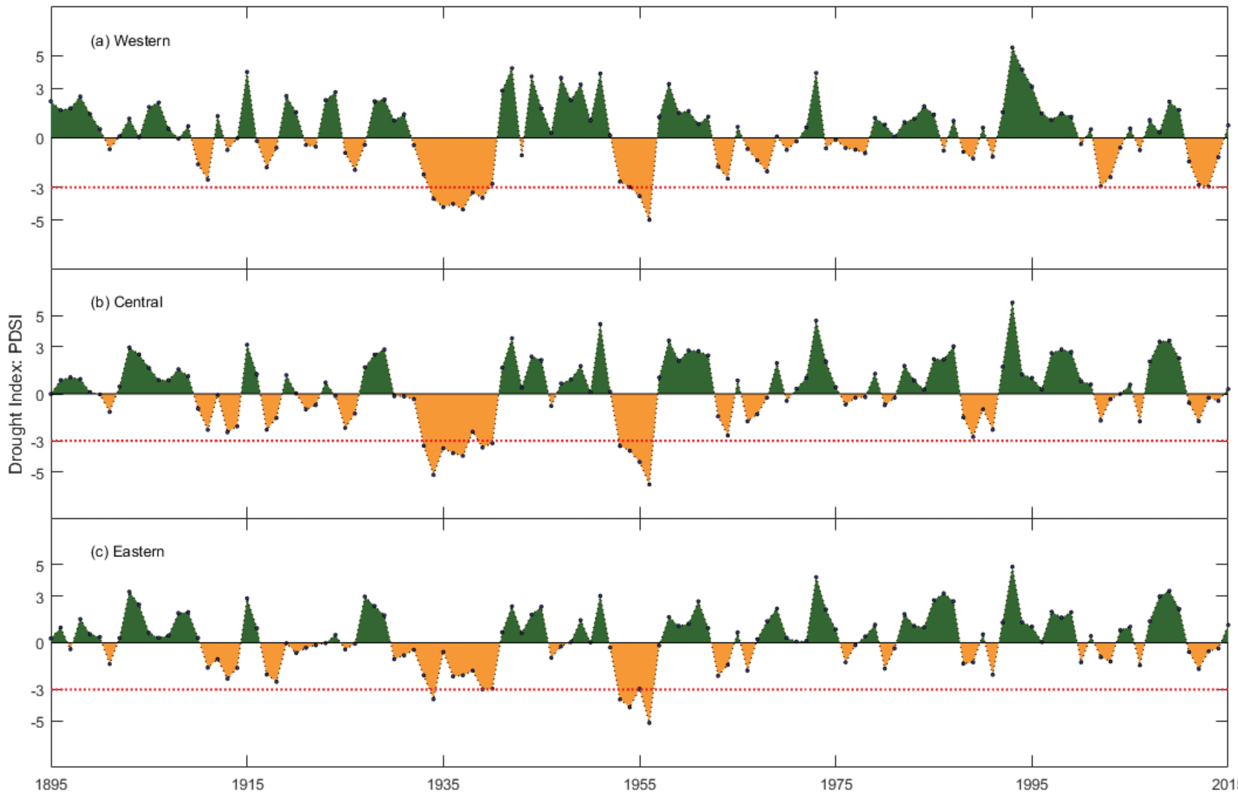

Figure 6. Average annual Palmer Drought Severity Index (PDSI) from 1895 through 2015: (a) Western; (b) Central; and (c) Eastern thirds of Kansas. The more negative the PDSI, the drier (orange). On the opposite side, the more positive the PDSI, the wetter (dark green). The dotted red lines (PDSI = -3) are indicators of severe drought occurrence. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

difference between the hottest year and coldest year is about 2.7°C (5°F) in Kansas. Perhaps more significantly, the precipitation difference is 671 mm (26 inches) between the wettest and driest years, which is more than annual expected precipitation in central Kansas (Fig. 4b). These significant swings of temperature and precipitation make Kansas crop and livestock productions relatively vulnerable to changes of increasing climate extreme events in the short-term and/or longer-term perspectives, which will require that adaptive measures be taken for sustaining Kansas agricultural production.

Summary and Conclusions

Accurate, historical climate information is a key resource for managing Kansas water resources and improving agricultural production. As the climate of Kansas continues to vary over time, information on past conditions and ongoing trends will help those managing other climate-sensitive resources across the state. Average temperatures in Kansas have significantly trended up during the last 121 years, a period in which the daily minimum temperature increased faster than the daily maximum temperature. The warming rate in Kansas, 0.06°C per decade (0.11°F per decade), is comparable with the U.S. as well as global warming rates (approximately 0.07°C per decade, IPCC 2013). This nighttime warming might not directly drive evapotranspiration loss as a whole, but it could have significant impacts on crop production, especially for winter wheat (Lobell and Oritz-Monasterio 2007; Melillo et al. 2014; Zhang et al. 2015).

Both drought and frost-free-days metrics were derived from available temperature and precipitation data. The drought events in 2011, 2012, and 2013 in Kansas were significant but not unprecedented climate phenomena, as they fell within historical variability ranges. Long-term observed precipitation in the state did not exhibit

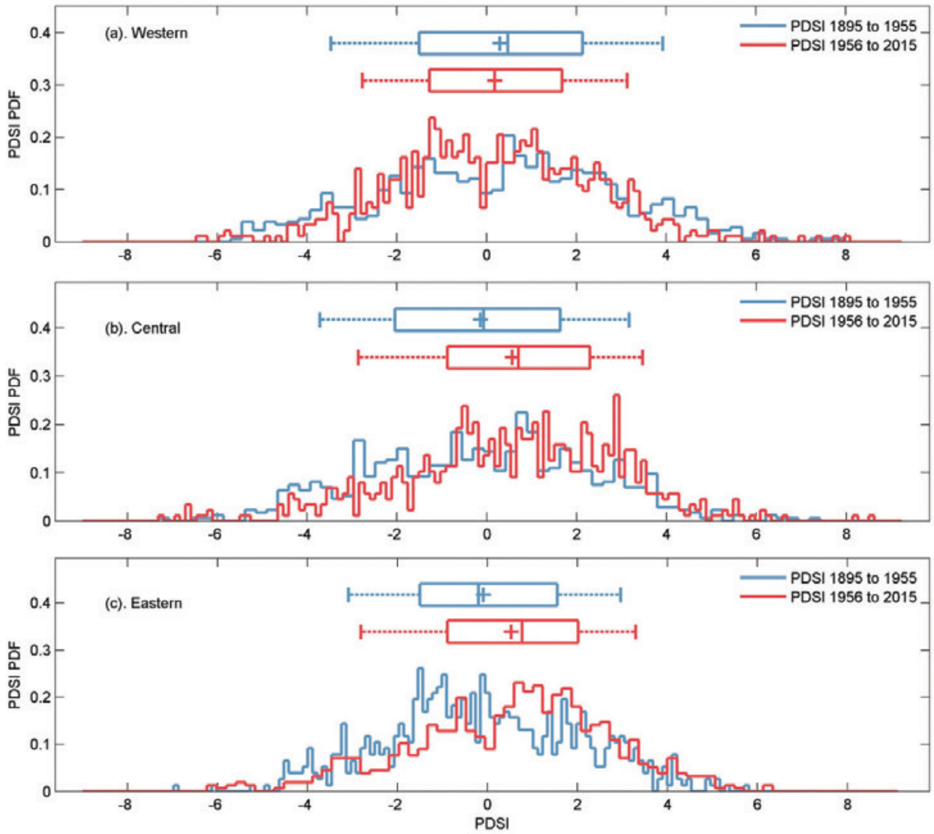

Figure 7. Probability density function (PDF) of Palmer Drought Severity Index (PDSI) during 1895 through 1955 and 1956 through 2015 in (a) Western; (b) Central; and (c) Eastern Kansas, respectively. The negative numbers to the left of "0" on the x axis represent drier-than-average conditions; the positive numbers to the right of "0" represent wetter-than-average conditions. Only in western Kansas is there a slightly drier-than-average pattern in the 1956 to 2015 period (red lines) compared to the 1895 to 1955 period (blue lines). In central and eastern Kansas, the most recent time period has been slightly wetter. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

any significant trends. Only western Kansas tended to be drier in more recent years, while central and eastern Kansas tended to be wetter. The temperature trends across Kansas have no obvious difference although climatology is distinctly different. Additional detail regarding these weak trends towards drier or wetter conditions could be valuable for Kansas water resource management interests. The frost-free season length, in contrast, demonstrated a clear and statistically significant increase across all of Kansas, with increases of 5.2 days in the west and 12.6 days in the east. These differences mirror the overall spatial trends of more warming in eastern Kansas, driven primarily by nighttime temperatures.

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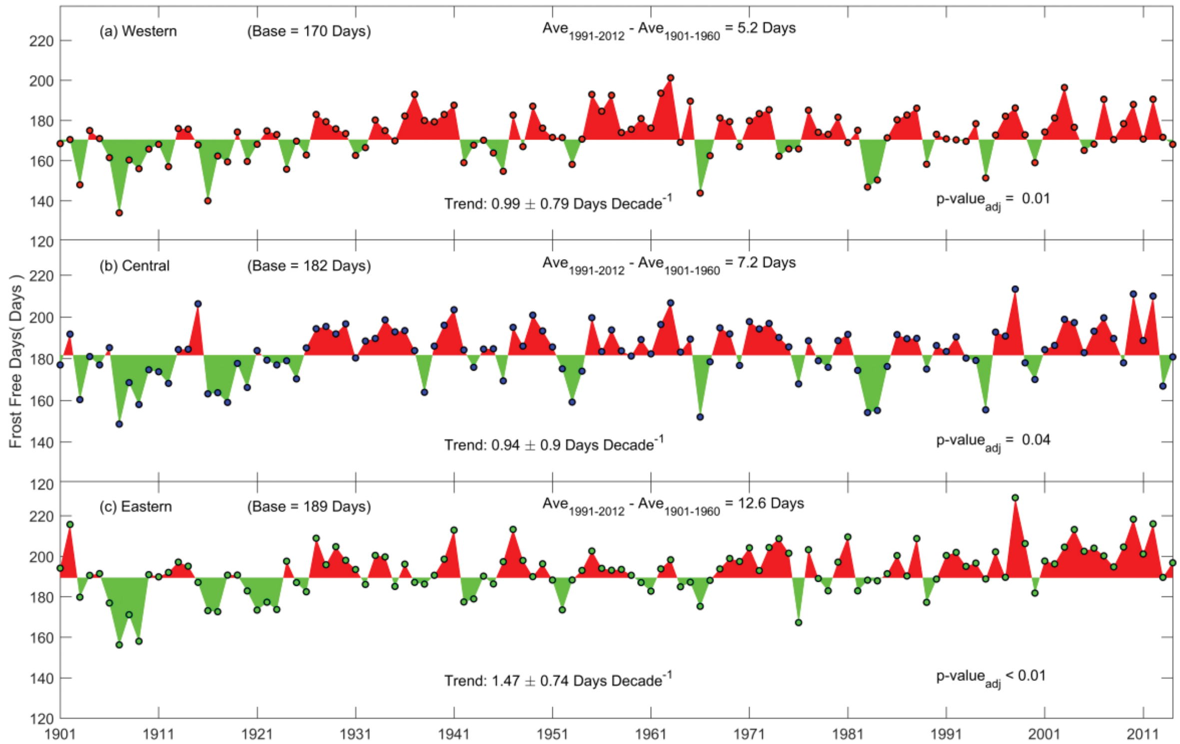

Figure 8. Time series of the frost-free season length in Kansas from 1901 to 2014: (a) Western; (b) Central; and (c) Eastern Kansas. The base indicates average number of frost-free days calculated from 1901 to 1960 (60-year period as a base period). The Ave 1991-2012 – Ave 1901-1960 is the difference of frost-free season length between 1991-2012 and 1901-1960. When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

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Irrigated Corn Production and Management in the Texas High Plains

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Abstract: Corn is the major irrigated crop in the Texas High Plains (THP) and uses 53% of the total agricultural regional water resource budget. Currently, the declining water level of the Ogallala Aquifer, coupled with irrigation pumping restrictions by regional groundwater conservation districts, is challenging sustainable, high level corn production. The objective of this article is to review production levels and evaluate corn management practices in the THP with reduced or limited levels of irrigation. Long-term field studies demonstrate that yield and water use efficiency (WUE) have increased significantly over the last forty years while seasonal corn evapotranspiration (ET) under full irrigation conditions has not increased. Among management practices, irrigation remains the single-most important factor in corn production. With recent advances in corn breeding and genetics, irrigation requirements can be reduced by up to 25% in some years and result in similar yields as compared to irrigation amounts at the 100% ET level. Also, WUE is generally maximized at irrigation levels meeting 75-80% ET demand. Newly developed drought tolerant corn hybrids have been shown to provide yield benefits of 10-15% under limited (reduced) irrigation water levels. At the higher irrigation levels (75-100% ET requirement), corn yield increased as seeding rate increased initially but did not increase further when the seeding rate exceeded 94,000 seeds ha^{-1}. Also, a multi-year planting date study indicated that high corn yields can still be achieved with a long-season hybrid when planted in the middle of May and early June. When the planting date is delayed to late June and early July, mid- and short- season hybrids showed a yield advantage over the long season hybrids.

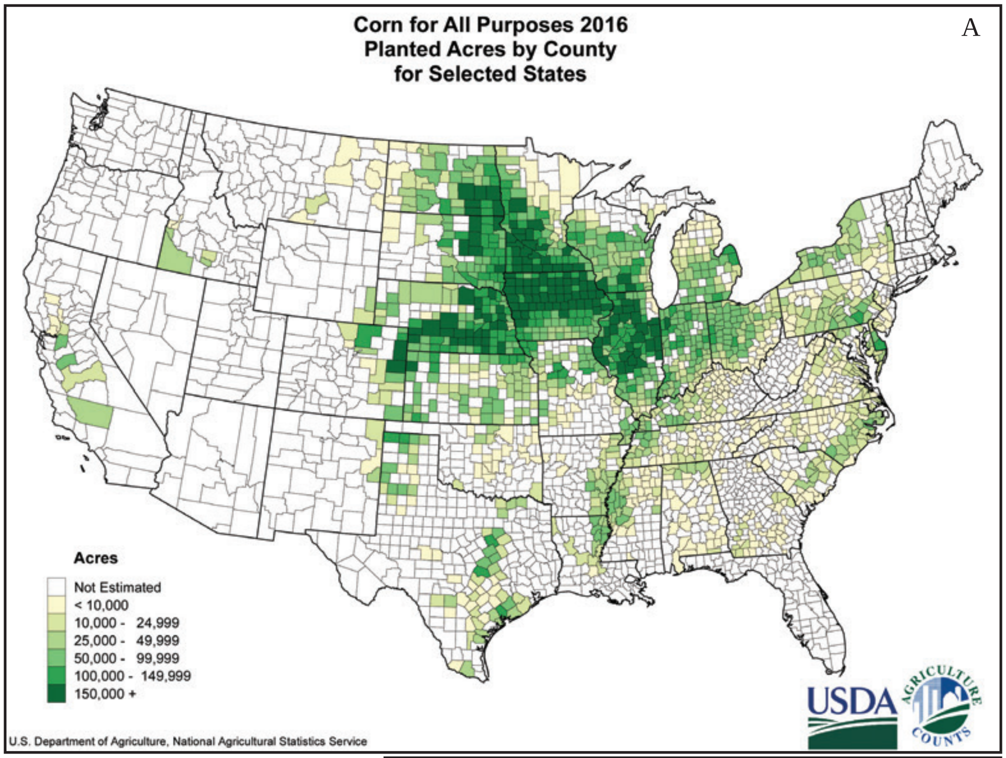
Keywords: *drought stress, drought tolerance, irrigation, water use efficiency, limited water, evapotranspiration, water use, Zea Mays L., crop ET*

The Texas High Plains (THP) is one of the most productive agricultural regions in the U.S. From 2009 to 2012, the Texas panhandle portion of this region had 58% corn, 41% wheat, 20% grain sorghum, 13% cotton, 63% ensilage, and 10% forage crops of the crop production in the State of Texas. Together with other crops and forages, the annual economic value of crop production in the region was nearly $1.7 billion, with corn production alone accounting for 40% ($688 million) of the total crop value (Amosson et al. 2015). In 2016, 2.9 million acres of corn were planted in Texas and nearly half of the state acreage (1.4 million acres) was in the THP region (Figure 1) (NASS 2016a, b).

In the THP, high corn productivity has heavily relied on irrigation for consistency and profitable operations. Among the major crops, corn uses 53% of the entire regional water budget annually for irrigation (1.76 billion m^3). Almost all irrigation in the THP is from the Ogallala Aquifer, with development of irrigation in this region significantly increasing since the 1950s. The Ogallala Aquifer is a finite water resource with minimal recharge, and the dramatic increase in water extraction for crop irrigation has resulted in significant decline of aquifer capacity with some areas experiencing a 50% or greater reduction in saturated thickness. Irrigated land area has decreased from a peak of 2.4 million ha in 1974 to 1.9 million ha in 2000 (Colaizzi et al. 2009). Therefore, sustained corn production faces challenges as THP irrigation water resources continue to decline. The development of profitable management strategies with limited irrigation scenarios is important for reducing production risk, maintaining profitability, and conserving water resources. The objective of this article is to review production levels and evaluate corn management practices in the THP with reduced or limited levels of irrigation based on long-term field experiments at Bushland and Etter, Texas.

Corn Yield, Evapotranspiration, and Water Use Efficiency

Figure 2 shows changes in corn yield from the mid-1970s to recent years at three levels (national, THP county average, and Research & Demonstration (R&D) plots) (Musick and Dusek 1980; Howell et al. 1995, 1996; Yazar et al. 1999; AgriPartners 2007; Colaizzi et al. 2011; Hao et al. 2015). The yield data from THP county and



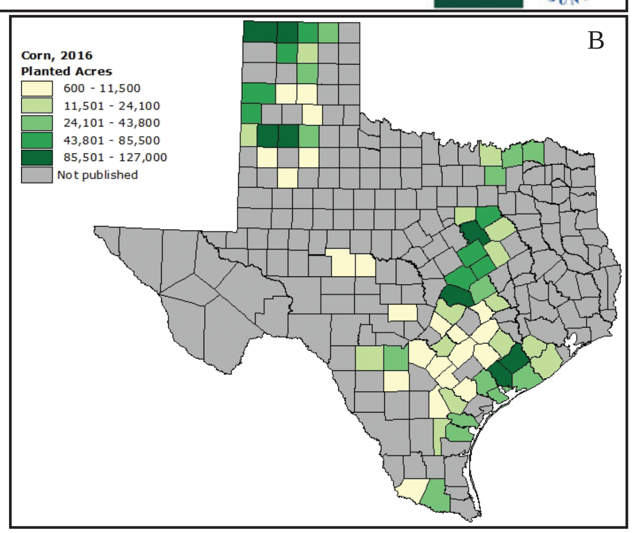


Figure 1. Corn planted acres in (A) the U.S. and (B) Texas in the 2016 growing season. (View originals at: (A) https://www.nass.usda.gov/Charts_and_Maps/graphics/CR-PL-RGBChor.pdf; (B) https://www.nass.usda.gov/Statistics_by_State/Texas/Publications/County_Estimates/ce_maps/ce_corn.php.)

R&D level were largely conducted at the 100% ET demand level. The national average corn yield was compiled from combined irrigated and rain-fed yield data. Although corn yield varied from year to year, there was a clear trend that yield has increased linearly over the last 40 years, with an annual increase of about 120 kg ha^{-1}. Interestingly, the slope of the increase is virtually the same at all three levels. Figure 2 shows that corn yield at the county level in the THP was always higher than the national average, and that the THP corn yield increased more than the national and R&D levels. At the county level, average yield increased from about 6-8 Mg ha^{-1} in the 1970s to about 13 Mg ha^{-1} in recent years (e.g., 2013). Corn yields of the R&D plots were higher than those of the county level, ranging from about 8 Mg ha^{-1} in 1970s to 16 Mg ha^{-1} in recent years (e.g., 2011-2013). The higher yield of the R&D plots is generally due to the smaller, more intensively managed production areas, as compared to field based production practice.

Corn has a high evapotranspiration (ET) demand (both daily and seasonally) in the THP (Howell et al. 1995, 1996). Daily corn ET has been measured in large, monolithic weighing lysimeters at Bushland, Texas, and often exceeds 10 mm d^{-1} for significant periods of time (Figure 3) (Howell et al. 1996). In contrast, daily ET rarely exceeds 10 mm d^{-1} in the central Great Plains of Nebraska (Grassini et al. 2011). Seasonal ET requirement for corn under varied irrigation levels has been studied at Bushland, Texas since the 1970s. Early studies under furrow irrigated conditions showed that seasonal ET ranged from 667 mm to 984 mm under full irrigation (Musick and Dusek 1980; Eck 1984). Field studies using sprinkler irrigation showed that seasonal ET ranged from 750-973 mm (mostly between 800-900 mm) in the 1990s at irrigation of 100% ET requirement (Howell et al. 1995, 1996; Schneider and Howell 1998; Yazar et al. 1999; Evett et al. 2000). Corn ET levels in producer's fields had a larger variation and ranged from 750 mm to 1200 mm. In recent studies at both

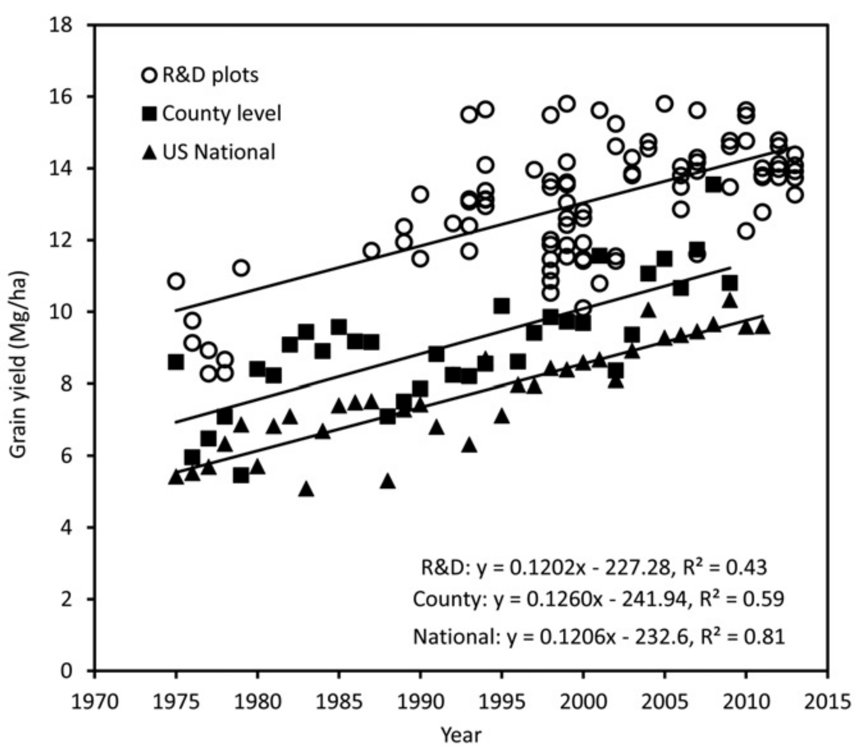


Figure 2. Corn yield from 1975 to recent time at National level, County level (average of top 26 counties in the Texas Panhandle), and Research and Demonstration (R&D) plots in the Texas High Plains. (Data sources: NASS; long-term field studies at Bushland and Etter, TX).

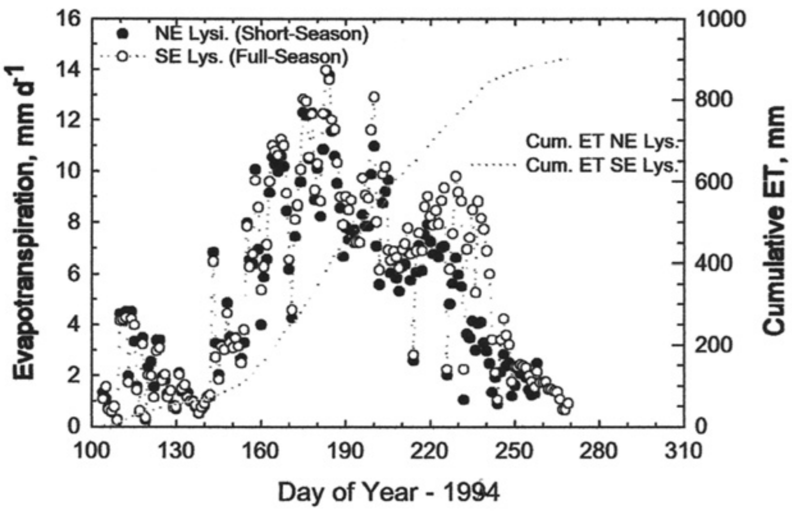


Figure 3. Daily evapotranspiration (ET) of fully irrigated corn at Bushland, TX in 1994 in lysimeters. NE lysimeter has a short-season hybrid, and SE lysimeter had a full-season hybrid (Howell et al. 1996).

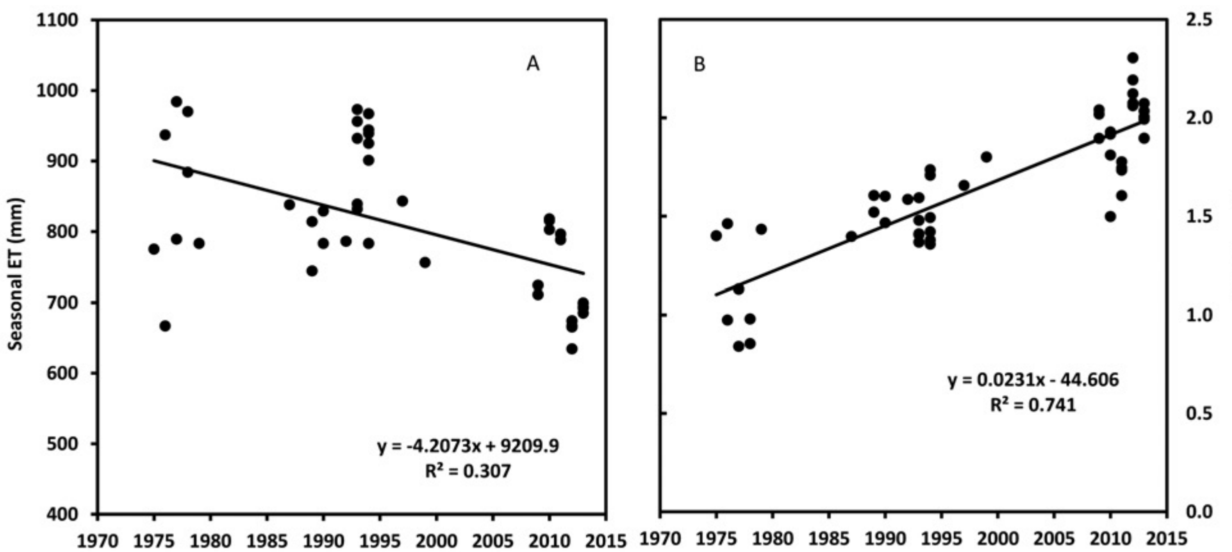


Figure 4. Changes of (A) seasonal evapotranspiration (ET) and (B) water use efficiency (WUE) under full irrigation conditions from 1975 to 2013 in the research plots (Data sources: long-term field studies at Bushland and Etter, TX).

Bushland and Etter, Texas, a lower seasonal ET was recorded under full irrigation at Etter than at Bushland. The ET is generally higher in the south than north, and in the east than west, in the THP region. Colaizzi et al. (2011) conducted a three-year experiment using a subsurface drip irrigation system and seasonal corn ET ranged from 711 mm to 818 mm at Bushland at irrigation level of 100% ET requirement. Hao et al. (2015) showed that corn under irrigation of 100% ET requirement ranged from 634 mm to 796 mm, depending on year and hybrid. Figure 4 shows that seasonal corn ET has a decreasing trend while WUE varied linearly over the years under full irrigation (100% ET requirement or greater) in the THP. In comparison, seasonal corn ET under full irrigation in other regions of the Great Plains was generally less than that in the THP, according to Rudnick et al. (2017) who summarized irrigation studies across the central and southern Great Plains from Nebraska and Colorado to Texas. In Nebraska, seasonal corn ET under full irrigation ranged from 526 mm to

655 mm in several field studies (van Donk et al. 2012; Irmak et al. 2015a, b; Rudnick et al. 2016).

The yield-ET relationship and WUE in corn have been reported in different studies at Bushland and Etter, Texas at different irrigation levels (Musick and Dusek 1980; Howell et al. 1995, 1996; Yazar et al. 1999; Colaizzi et al. 2011; Hao et al. 2015). For comparison, an analysis of the corn yield-ET relationship was used using three data sets, representing differing time periods in the THP. The first data set was from Musick and Dusek (1980). They conducted field studies at different furrow irrigation levels and frequencies from 1975 to 1977. The second data set was compiled from a field study using center pivot sprinkler irrigation in 1994 and 1995 (Schneider and Howell 1998). The third data set was from recent field studies conducted at Etter, Texas from 2011 to 2013 using different hybrids and planting densities (Hao et al. 2015). During all three time periods, corn yield increased linearly as seasonal ET increased (Figure 5). Linear regression between corn yield and ET resulted in a slope of 0.0243, 0.0277, and 0.0285 (the unit is Mg ha^{-1} mm^{-1}) in the studies of 1975-1977, 1994-1995, and 2011-2013, respectively. Based on the three linear equations in Figure 5, a threshold ET can be calculated for each study. Threshold ET is the ET level at which the first grains are initiated (Musick et al. 1994; Schneider and Howell 1998). The threshold ET value was 346 mm for the 1975-1977 study, 310 mm for the 1994-1995 study, and 214 mm for the 2011-2013 study. Schneider and Howell (1998) summarized the slopes of the linear regressions of yield and ET and threshold ET values in different studies conducted at Bushland, Texas. The slopes ranged from 0.02 to 0.34 and the threshold ET values ranged from 147 mm to 467 mm (Schneider and Howell 1998). Although the smaller threshold ET value in the 2011-2013 study (214 mm) may indicate management improvement over the decades as compared to the 1975-1977 study (346 mm), the yield-ET relationship can be affected by many factors. Nevertheless, comparing yield and ET in the three studies, corn yield increased at any ET level from 1975 to 2013, indicating overall

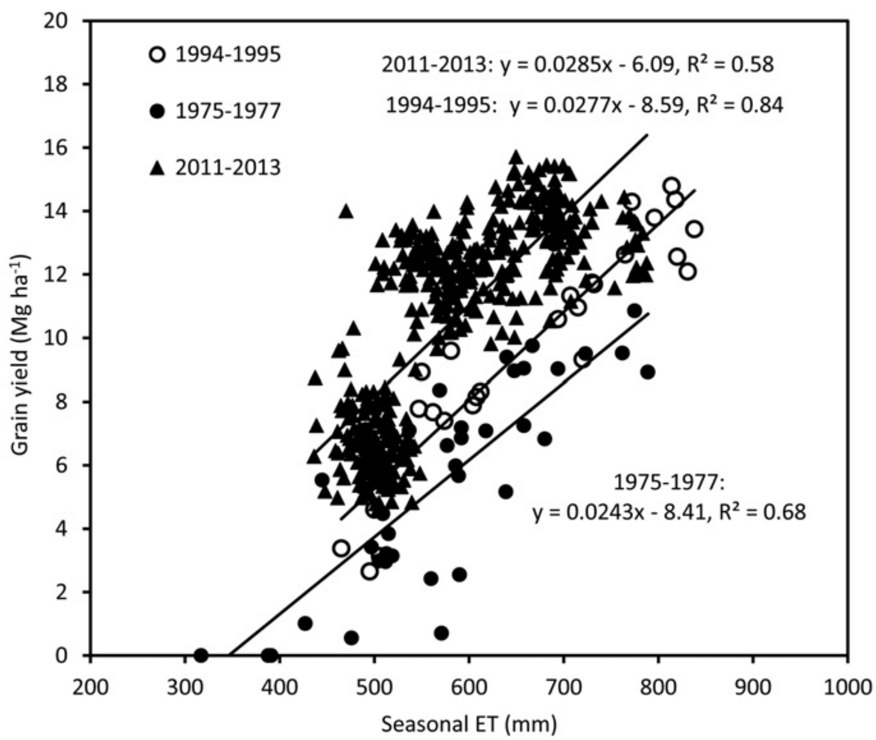


Figure 5. The relationship between corn yield and seasonal evapotranspiration (ET) in the periods of 1975-1977, 1994-1995, and 2011-2013 in the Texas High Plains (Data sources: Musick and Dusek 1980; Schneider and Howell 1998; Hao et al. 2015).

corn yield improvement in the last four decades. Greater yields in the studies of 1994-1995 and 2011-2013 at lower ET levels (<600 mm) indicate that drought tolerance technology in new corn hybrids has improved in the last four decades. The improvement of drought and other stress tolerance in corn hybrids has also been reported in the U.S. Corn-belt region and Canada (Tollenaar and Lee 2002; Hammer et al. 2009).

As WUE is the ratio of yield to seasonal ET, factors affecting both yield and ET will affect the WUE values. In the THP, WUE values were affected by irrigation amount, frequency, and management methods (Howell et al. 1995; Schneider and Howell 1998; Hao et al. 2015). Under full irrigation conditions (100% ET requirement or greater), WUE has increased from about 1.00 kg m^{-3} in the 1975-1977 study to about 2.00 kg m^{-3} in the 2011-2013 study (Figures 2, 4). The increased WUE in recent years (2011-2013) reflects the yield improvement over the last four decades. Studies have also shown that the maximum WUE is generally achieved at less than the 100% ET requirement level (Howell et al. 1995; Payero et al. 2008; Colaizzi et al. 2011; Hao et al. 2015). Corn WUE at the 100% ET level and 75% ET level ranged from 1.80 to 2.17 kg m^{-3} at Bushland (Colaizzi et al. 2011). WUE values at the same two irrigation levels ranged from 1.51 to 2.57 kg m^{-3} with a relatively low WUE (1.51-2.15 kg m^{-3}) in 2011 and a relatively large WUE (1.70-2.57 kg m^{-3}) in 2012 and 2013 in a study at Etter, Texas (Hao et al. 2015). In a two-year (1992 and 1993) field study at Bushland Texas, a lower corn WUE of 1.58-1.75 kg m^{-3} was reported by Howell et al. (1995). However, WUE decreased significantly as irrigation levels were reduced to 50% ET requirement or less (Schneider and Howell 1998; Hao et al. 2015). For example, irrigation at the 25% ET level can result in crop failure (Schneider and Howell 1998).

Irrigated Corn Management Practices in the Texas High Plains

A declining water table coupled with irrigation pumping restrictions by groundwater districts could challenge sustainable corn production in the region. Limited irrigation, the application of less irrigation water than the plants require for full crop ET (100% level), will be the primary practice in the future in the THP. As such, development of advanced management practices is important to continue improving the yield and WUE relationship under water-limited conditions. Generally, there are two approaches to improve crop performance: breeding and management practices. Improving corn yield and WUE through breeding has been a major focus in both private (Pioneer, Monsanto, and Syngenta companies) and public sectors (e.g., universities). Management practices are as important, or possibly more so, than breeding when water-limited conditions exist (Passioura and Angus 2010). Improved crop management is responsible for the larger portion of increased productivity under water-limited conditions (Anderson 2010).

Irrigation Management

Although many management factors affect corn production in the THP, irrigation management remains the most effective way to sustain high crop productivity. In the THP, irrigation systems and accommodating agricultural practices have changed significantly in the last four decades, from furrow irrigation (1950s-1970s) to center pivot sprinkler and to (a lesser degree) subsurface drip irrigation systems that are currently being used. The history and trends of irrigation research and development in the region have been reviewed in different eras from the 1990s to recent time (Musick et al. 1990; Colaizzi et al. 2009; Evett et al. 2014). The details of irrigation history, economic impact, research, and development trends can be found in the aforementioned three review papers. Based on these papers, there are three generally inferred statements regarding irrigation in the THP. First, the irrigation supply from the Ogallala Aquifer is declining. Second, irrigation efficiency through systems conversion has been dramatically increased over the last few decades in the THP. Third, the future challenge is how to efficiently use the reduced amounts of irrigation while sustaining corn yields. The last is further challenged by the fact that future increases in other regional needs (such as municipal demand, power generation, etc.) will be added to the expense of the irrigation supply (PWPG 2011). However, preserving irrigation is crucial to sustainable crop production in the region (as well as national security item) since irrigation significantly increases WUE as compared to dryland production (Evett et al. 2014).

To increase the efficiency of the irrigation applications, events should be scheduled using measurements of ET, soil moisture depletion, and/or plant based measurements. Irrigation scheduling to enhance the WUE includes the management of both water and soils. Crop ET is typically calculated using a crop specific coefficient (Kc) and reference evapotranspiration (ET_o). ET_o is calculated evapotranspiration from a reference crop (turf grass or alfalfa) using the meteorological parameters of temperature, relative humidity, precipitation, wind speed, and solar radiation. Irrigation can also be scheduled according to changes in soil moisture. Soil moisture sensors can provide information on soil moisture fluxes in the root zone, which provide information on when to initiate and terminate irrigation events. Irrigation scheduling using ET, a soil water balance method, or a combination of the two can be successfully employed in irrigated corn production.

The seasonal average irrigation for (grain) corn is approximately 500 mm in the THP Region A (Top 26 Counties of Texas, Marek et al. 2011). However, irrigation demand can vary and be much higher during a severe drought year such as in 2011, with a seasonal ET of 900 mm and irrigation of 754 mm (Hao et al. 2015). Based on multiple-year studies at Bushland and Etter, using irrigation to meet a 75-80% of ET demand level can result in similar yields as compared to years where 100% of the ET demand was achieved with average or above average seasonal rainfall. Also, WUE is generally maximized at the 75-80% irrigation level. Unless adequate seasonal rainfall (normally > 250 mm) and excellent soil water storage exist at the time of planting, lowering irrigation levels to a 50% ET requirement or less significantly reduced corn yield (Schneider and Howell 1998; Collaizzi et al. 2011; Hao et al. 2015). Irrigation levels at the 25% ET level can result in yield failures based on studies conducted by Schneider and Howell (1998) and Colaizzi et al. (2011).

Hybrid Selection

Hybrid selection is another impacting factor for corn producers and is increasingly becoming different from choices of the past. Drought and irrigation system capacity remain the most important producer concern in the THP. Figure 5 shows that corn yield has increased sufficiently at lower ET levels from 1970s to the present, indicating corn drought tolerance has improved. Drought tolerance has been considered (and marketed) as an important component in the success of corn hybrids grown in semi-arid or arid regions such as the THP and western Cornbelt (Cooper et al. 2014). Studies conducted at Etter, Texas demonstrated that recently released drought-tolerant AQUAmax hybrids P1151HR and P1564HR consistently showed yield benefit as compared to a conventional hybrid (33D49) at lower irrigation levels (75% and 50% ET demands), especially under severe water stress conditions (e.g., 50% ET demand; Hao et al. 2015). Comparable results were found by Cooper et al. (2014), who reported that AQUAmax hybrids showed higher grain yield than regular drought-tolerant and drought-sensitive hybrids under drought conditions.

Breeding for drought tolerance in corn is a major goal to improve yield stability under drought conditions. Furthermore, corn yield performance under non-drought conditions should also be considered when breeding for drought tolerance since producers are unlikely to adopt drought-tolerant hybrids if there is a significant yield penalty in well-watered environments (Boyer et al. 2013). Hao et al. (2015) showed that AQUAmax hybrids (P1151HR and P1564HR) had greater grain yield than the check hybrid (33D49) at irrigation levels of 75% and 50% ET demands. However, no significant yield penalty was observed with either P1151HR or P1564HR at the 100% ET levels (Hao et al. 2015). Although the newly developed drought tolerant corn hybrids provide significant yield benefits (10-15%) under lower irrigation levels, a conventional new hybrid would yield the same as drought tolerant hybrids if there was sufficient water.

Seeding Rate

Due to the high corn seed prices, producers are concerned about seeding rate. Regarding corn seeding rate in the U.S. and Canada, only about 10% of corn acreage is planted at 89,000 or more seeds per hectare. About a third of the corn area planted is at 81,000 to 89,000 seeds per hectare (Butzen 2016). Marek et al. (2016) evaluated interactions of hybrids and seeding rate at multiple irrigation levels. The seeding rate ranged from 64,000 to 138,000 seeds per hectare. At the 100% ET level, corn yield increased as population increased initially but did not increase further at populations higher than 94,000 or 109,000 seeds per hectare, depending on hybrids (Marek et al. 2016). An optimal economic seeding rate (a seeding rate where yield increase from the next increment of seed no longer exceeds the seed cost) increased as yield potential increased. For example, the economic optimum seeding rate was determined to be 77,000 seeds ha^{-1} for 9.4 Mg ha^{-1} corn yield, but it increased to 96,000 seeds ha^{-1} for 15.1 Mg ha^{-1} yield. Based on published literature and the trial results of Marek et al. (2016), a rate of 99,000 seeds ha^{-1} or less would be sufficient for corn in the THP if the yield target is about 15.6 Mg ha^{-1}.

Planting Date

Corn planting dates in the THP range from mid-April to late May. Field trials were conducted and planting date and hybrid interaction for corn yield and water use were evaluated (Xue et al. 2014). The planting dates tested were May 15, June 1, June 15, and July 1. The results from this study indicated that high yield (13 Mg ha^{-1}) can still be achieved with a longer-season hybrid (e.g., > 111-day) when planted from mid-May to early June. When the planting date was delayed to late June and early July, corn yields were significantly reduced (about 3.6-7.7 Mg ha^{-1}, depending on the hybrid) for the long-season hybrids. However, yields in a short-season hybrid (96-day) were relatively consistent (8-10 Mg ha^{-1}) as planting date was delayed to late June. Although delaying planting to late June or early July could reduce corn yield potential, late planting can save irrigation water while maintaining greater water use efficiency.

Future Perspectives

Although progress has been made to improve corn yield and WUE in the last few decades in the THP, corn production still faces formidable challenges with declining irrigation water resources and from the additional potential of abiotic stresses suggested by climate change and the increased risk of frequent droughts. The amount of irrigation water available for corn production in the THP continues to decline. Although irrigation technologies have been dramatically improved over the years, management and genetic improvement are foreseen as extremely important in corn production. Drought stress is typical during the corn growing season with limited irrigation in semi-arid and arid regions, so improving both heat and drought tolerance through breeding will be an important component of overall crop improvement. Current research efforts have focused on grain yield, but very little attention has been given to grain quality including mycotoxin contamination. High mycotoxin levels can lead to the rejection of grains and as a result cause the WUE to decline to almost zero in the economic aspect. An improved understanding of crop response to drought stress factors and the identification of plant traits as affected by each will lead to the development of improved germplasm and hybrids in this region. It is also envisioned by many that additional supporting data using unmanned aerial systems (UAV's) should aid in the assessment of these characteristics and improve limited water production and management practices, particularly with the more water sensitive crops such as corn.

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Crop Water Production Functions of Grain Sorghum and Winter Wheat in Kansas and Texas

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Abstract: Productivity of water-limited cropping systems can be reduced by untimely distribution of water as well as cold and heat stress. The objective of this study was to evaluate the predictive accuracy of the Kansas Water Budget (KSWB) model for crop water use and grain productivity of grain sorghum and winter wheat grown in a range of crop sequences. The relationship of grain yield to crop water use, reported in several crop sequence studies conducted in Bushland, TX, and Colby and Tribune, KS, was compared against the KSWB modeling results. Field studies showed that the yield responses of grain sorghum to an increment of water use was generally 75% greater than that of winter wheat, as expected for crops with C4 and C3 physiology, respectively. The relationship of winter wheat yield to crop water use, simulated by the KSWB model, was comparable to relationships developed in four of five studies, with the exception of one study conducted in Bushland that suggested less crop water productivity. For grain sorghum, experimental yield response to an increment of water use was less than that calculated for three of five cases; for one study at Colby and Tribune, simulated and experimental yield response to water use were similar. Simulated yield thresholds were consistent with observed yield thresholds for both wheat and sorghum in all but one case. The KSWB model provides a useful analytic framework for distinguishing water supply constraints to grain productivity.

Keywords: *crop yield, water budget model, cropping system, Kansas, water*

Productivity of water-limited cropping systems in the High Plains is controlled by many factors. Grain yields for dryland crop production systems in the semiarid Great Plains of the United States are difficult to predict because of the variable distribution of growing season precipitation (Nielsen et al. 2010). Water deficits can affect productivity at specific growing periods throughout the crop season and in the overall total supply of water (Brown 1959; Passioura 2006). Generally, the timing of water supply has a larger effect on grain yield than total water supply, for many crops (Maman et al. 2003). Weeds, diseases, pests, and extreme weather events can destroy crops and limit productivity as well. Climate change could also contribute to changes of crop productivity (Tao and Zhang 2013). The frequency of years when temperatures exceed the thresholds for crop damage is likely to increase for some crops and regions (Hatfield et al. 2013). In a western Kansas study, Stone and Schlegel (2006) found a positive relationship between grain yield of wheat and sorghum, with both available soil water at emergence (22.1 kg ha^{-1} mm^{-1} available soil water), and in-season precipitation (16.4 kg ha^{-1} mm^{-1} in-season precipitation). They found similar yield responses for winter wheat (9.8 kg ha^{-1} mm^{-1} available soil water and 8.3 kg ha^{-1} mm^{-1} in-season precipitation). The greater yield responses of grain sorghum were expected due to more effective carbon gain per water loss associated with the C4 physiology of sorghum, compared with the C3 physiology of wheat. In the same study, 63% of grain sorghum and 70% of winter wheat variations in grain yield were explained by variations in available soil water at emergence and in-season precipitation. Because of the high input costs for production, farmers can benefit from a tool that will help them assess the risks associated with dryland crop production (Nielsen et al. 2010).

Grain sorghum and winter wheat are the primary dryland crops in the semiarid regions of the High Plains (USDA Census of Agriculture 2012). The precipitation pattern of a region influences the cropping sequence used in order to maximize the use of rainfall received (Sherrod et al. 2014). Grain sorghum and winter wheat are important crops in the High Plains region due to their drought resistance and ability to produce under limited precipitation. Dryland production is regaining its importance in this region as irrigated crop production decreases due to groundwater depletion (Steward et al. 2013). Diverse (more crop types) and intensive (more crops in a period of time) cropping systems have the potential to improve crop production without increasing inputs (Tanaka et al. 2005). Peterson et al. (1996) found that the most direct and practical solution for increasing precipitation use efficiency may be to include a summer crop following winter wheat that would make better use of summer precipitation. They also found that dryland cropping systems with more diverse crops and less fallow per unit time may be one strategy to make more efficient use of precipitation lost to evaporation during fallow.

While there are multiple environmental variables controlling crop yield, comparing actual to expected yield can still be instructive (Passioura 2006). Models can be used to calculate an estimated yield based on a soil water balance equation. It can be challenging to understand the interactions of changing climatic variables because of the interactions among temperature and precipitation on plant growth and development (Hatfield et al. 2013). Crop species respond differently to the timing of rainfall and need to be evaluated separately (Sherrod et al. 2014). Water use-yield relationships are the foundation for efficient water management (Siahpoosh and Dehghanian 2012). These relationships can be developed by simulating the field water balance, including simulated drainage for each location (Stone et al. 2011). Mathews and Brown (1938) related crop yield to water use for winter wheat in the southern Great Plains and reported a wheat water productivity of 5.19 kg ha^{-1} mm^{-1} with a yield threshold (the level of water use where yield response begins) of 187 mm. Aiken et al. (2013) reported that in Colby, KS, wheat water productivity was 9.97 kg ha^{-1} mm^{-1} with a yield threshold of 110 mm, and Nielsen et al. (2011) reported an even greater wheat water productivity of 12.49 kg ha^{-1} mm^{-1} with a yield threshold of 132 mm for northeast Colorado. The difficulty in measuring the components of the soil water balance encourages the use of simulation models to investigate the processes involved (Lascano 1991). Process-based modeling can be used to investigate separate parts of the system and can also be used as a tool to investigate solutions to crop production problems, which are normally site-specific (Lascano 1991). Models are representations of complex systems and do not include every environmental factor that can influence yield, but they can still be useful in order to observe and understand relationships between water use and grain productivity. The Kansas Water Budget (KSWB) model solves the soil water balance and calculates actual evapotranspiration, drainage, and crop water use. The model uses crop production functions to estimate yields (Khan et al. 1996). The objective of this study was to evaluate the predictive accuracy of the model for crop water use and grain productivity of grain sorghum and winter wheat grown in a range of crop sequences.

Methods

The predictive accuracy of a modified form of the KSWB (Stone and Schlegel 2006) model was evaluated through two variables: crop water use and yield. The KSWB model was modified to include non-crop periods while maintaining continuity of the soil water balance needed to simulate multi-crop sequences for multiple years. Each of these values was calculated for grain sorghum and winter wheat using different sites, years, and crop rotations. Modeled crop water use and yield data from three sites (Bushland, TX; Colby, KS; and Tribune, KS) were compared with experimental water use and yield data for each crop in order to determine how accurately experimental data could be modeled. Crop water use and yield were then used to generate functional relationships showing yield response to an increment of water use, where yield was the dependent variable and water use was the independent variable. This function was used to find the yield threshold, which is the level of water use where yield response begins.

The KSWB model (Khan et al. 1996) solves the water balance with a daily time step. To calculate the daily total water content of the soil profile, it is necessary to include a water balance equation:

$$SW_i = SW_{i-1} - ET_{a_{i-1}} - DR_{i-1} + EPR_{i-1} \qquad [1]$$

where i is the day of the year and $i\text{-}1$ is the previous day of the year, SW is the total soil water in the profile (mm), ET_a is the daily actual evapotranspiration taken out of the profile (mm), DR is the daily amount of drainage coming out of the bottom of the profile, and EPR is the effective precipitation (mm), which is daily precipitation after taking out runoff. During model implementation, the first day of the soil water balance was initialized as the total soil water at planting as provided in the experimental data. If data were not provided, such as when the first year was a non-crop period, a value of 60% of available soil water was used. The model assumes stubble mulch tillage as the conventional tillage. A flowchart depicting the procedure of the KSWB model is shown in Figure 1.

Yields are calculated using crop production functions, which include an effective ET term. A crop's source of water is stored soil water, and if there is not sufficient water to meet a specific crop's water requirement, water stress develops in the plant which has a negative effect on photosynthesis, crop growth, and yield. Water stress does not have the same effect on crop yield at every crop growth stage. To account for this, weighting factors were assigned to each growth period. Weighting factors are different for each growth period of a crop depending on the sensitivity of the growth period to water stress. They relate yield with actual ET relative to maximum ET. The KSWB model divides the crop growing season into four growth

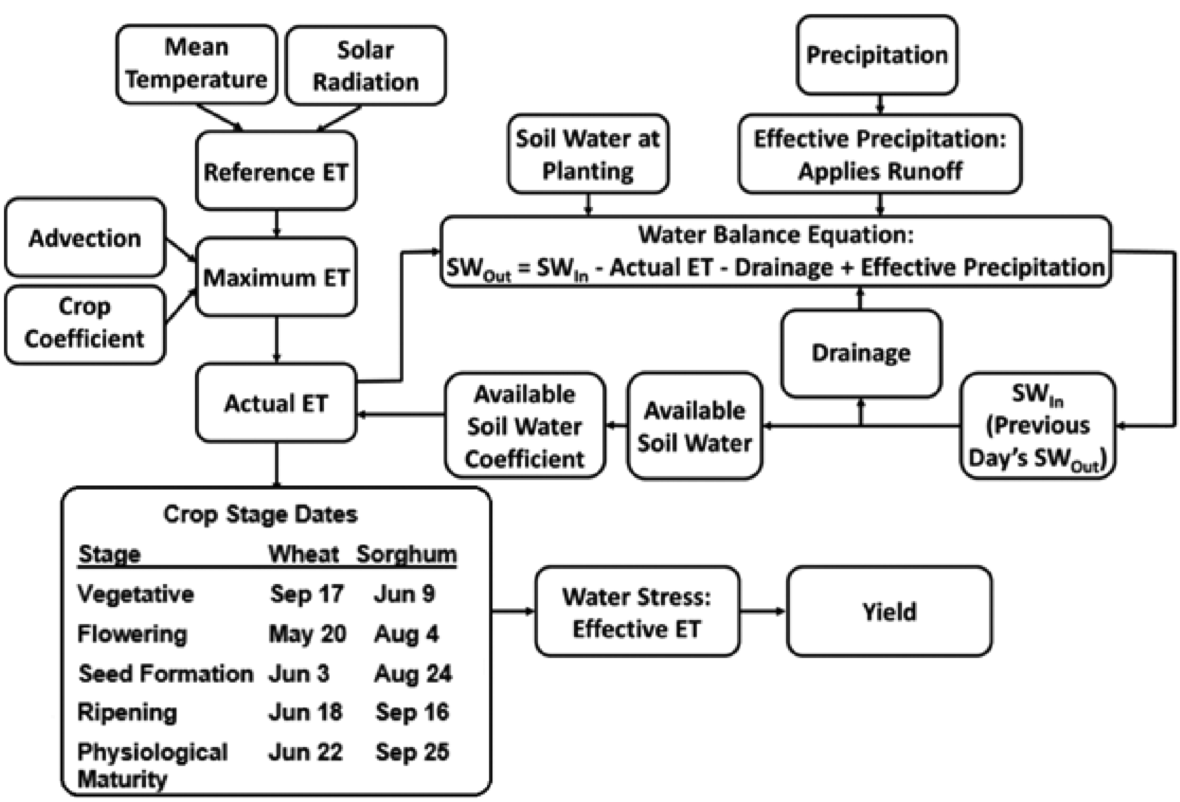

Figure 1. Kansas water budget (KSWB) flowchart. SW denotes soil water and ET is the evapotranspiration.

periods: vegetative, flowering, seed formation, and ripening. The effective ET is a sum of the weighted ET values for each of the four growth periods. The crop yield production function is:

$$Y = CWP \bullet (eET - YT) \quad [2]$$

where Y is yield (kg ha^{-1}), CWP is the slope of a crop water productivity function (kg ha^{-1} mm^{-1}), eET is effective ET (mm), and YT is yield threshold (mm), the quantity of expected eET corresponding to the onset of expected grain yield. Effective ET is used to represent a crop under water stress and can be calculated from:

$$eET = \sum mET_i \bullet \sum \left(w_i \bullet \frac{aET_i}{mET_i} \right) \quad [3]$$

where mET_i is maximum ET (mm) calculated by a Jensen-Haise relationship (Jensen and Haise 1963), corresponding to crop development stage 'i' (see Figure 1); w_i represents weighting functions (wheat: 0.49, 0.31, 0.19, and 0.01; grain sorghum: 0.44, 0.39, 0.14, and 0.03) corresponding to the crop development stages; and aET (mm) is ET calculated from the KSWB model.

Effective Precipitation

Effective precipitation was calculated daily in order to account for runoff:

$$EPR = P(1 - RF) \quad [4]$$

where P is precipitation (mm) and RF is the runoff fraction from either the equation:

$$RF = 0.106 + (0.000062 * AP^2) \quad [5]$$

for the Tribune and Colby, KS soils which are part of soil hydrologic group BC, or from the equation (Stone et al. 2006; Stone pers. comm.):

$$RF = 0.157 + (0.000072 * AP^2) \quad [6]$$

for the Bushland, TX soil which is part of soil hydrologic group C (Stone pers. comm.). In these equations, AP was the total annual precipitation in inches. This RF value was developed with corn as the base crop. In order to account for crop type, 0.01 is added to the base value to adjust for grain sorghum, and for winter wheat, 0.10 is subtracted from the base value.

The KSWB was modified to simulate multi-year crop sequences. The user initiates a simulation run by selecting a location, cropping sequence (continuous wheat - CW, continuous sorghum - CS, wheat-fallow - WF, wheat-sorghum-fallow - WSF, wheat-wheat-sorghum-fallow - WWSF, or wheat-sorghum-sorghum-fallow - WSSF), the starting year of the simulation, and the number of years to run the simulation. Weather data are compiled from the first day of the first crop phase to the last day of the last crop phase, so that for each day the model runs the correct weather data will be used. The total soil water (mm) in the soil profile at planting was used for the first crop at the beginning of the chosen sequence. At the start of each crop or non-crop phase, the water balance was calculated until the end of the phase, then switched to the next phase while changing the necessary parameters and carrying over the water balance. Upon completion of the final phase, the model was re-initialized at the first harvest year and the simulation was then run using the second crop in the crop sequence, if applicable. The user provided the soil water at planting for that crop. If it is a non-crop period (fallow in wheat-sorghum-fallow rotation), then the user can enter a 0, which was set into a default value of 60% of available soil water in the profile. The simulation was conducted until there was a harvest for each of the years specified by the user.

Field Studies – Experimental Data

Simulation results from the KSWB model runs were compared with experimental data from three locations. For each location, crop water use (CWU) was calculated as:

$$CWU = SW_i - SW_f + P \quad [7]$$

where SW_i is soil water at planting (mm), SW_f is soil water at physiological maturity (mm), and P is in-season precipitation (mm).

Table 1 shows the experimental data for all studies. The soil type at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll). The soil type at the Northwest Research-Extension Center in Colby, KS was a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustoll). The soil type at the Southwest Research-Extension Center near Tribune, KS was a Richfield silt loam (fine, smectitic, mesic Aridic Argiustoll). The crop

Table 1. Experimental data for all studies. Crop Sequences: CW - Continuous Wheat, CS - Continuous Sorghum, WF - Wheat-Fallow, WSF - Wheat-Sorghum-Fallow, WWSF - Wheat-Wheat-Sorghum-Fallow, and WSSF - Wheat-Sorghum-Sorghum-Fallow. Tillage: SM - Stubble Mulch, NT - No-Till, RT - Reduced Tillage, ST - Sweep Tillage.

Study Citation	Location	Crop Sequences	Duration	Soil Depth (m)	Tillage Practices
Jones and Popham 1997	Bushland, TX	CW, CS, WF, WSF	1984-1993	1.8	SM, NT
Schlegel et al. 2002	Tribune, KS	CW, WWSF, WSSF	1996-2000	1.8	CW and sorghum – NT, wheat following sorghum – RT
Aiken et al. 2013	Colby, KS	WSF	2002-2008	1.8	NT
Aiken Unpublished	Colby, KS	WSF	2007-2014	2.4	ST
Baumhardt and Jones 2002	Bushland, TX	WSF	1990-1995	1.8	SM, NT
Moroke et al. 2011	Bushland, TX	CS	2000-2001	2.4	SM, NT

water use and yield values using stubble mulch tillage were taken from the experimental data. Results from Moroke et al. (2011) and Baumhardt and Jones (2002) were combined due to similarity in site location, study period, and the limited number of site years. Tables 2 and 3 show starting and ending dates (planting and physiological maturity dates) for each crop and for each of the individual studies.

Modeling Measures

Simple linear least square regression models were developed and used to relate modeled results to experimental data for crop water use and yield for each crop at each location with a level of significance of 0.05. A t-test using standard error and n-1 degrees of freedom (where n is the number of points determining the regression) was used to test slope and intercept against a slope of one and an intercept of zero.

The Nash-Sutcliffe (NS) model was used to assess the predictive power of each model. It evaluated the deviation of observations from model predictions relative to deviations of observed values from their mean:

$$NS = 1 - \frac{\sum(Observed - Modeled)^2}{\sum(Observed - Mean\,(Observed))^2} \quad [8]$$

where *Observed* values are those from the experimental data, and *Modeled* values are those from the KSWB model. If the *NS* coefficient is 0, then the model predictions are as accurate as the mean of the observed data; a *NS* coefficient of 1 indicates perfect model performance. Marek et al. (2016) indicate that *NS* coefficients between 0.5 and 1 are generally considered acceptable. *NS* values between 0 and 0.5 are considered to have greater predictive skill than the mean value.

Crop water use and yield data were plotted together for both observed and modeled results for each crop at each location. Plots of the CWU-yield relationship were made for both modeled and observed values and were compared for both wheat and sorghum. Tests for linearity were done

Table 2. Starting and ending dates for wheat crop for experiments and for the Kansas Water Budget model.

Reference	Location	Planting Date	Physiological Maturity Date
Jones and Popham 1997	Bushland	Late September, Early October	Late June, Early July
Baumhardt and Jones 2002	Bushland	Late September, Early October	Early July
Aiken et al. 2013 Aiken Unpublished	Colby	September 17 to October 20	June 18 to July 3
Schlegel et al. 2002	Tribune	September	Late June, Early July
KSWB	-	September 17	June 22

Table 3. Starting and ending dates for sorghum crop for experiments and for the Kansas Water Budget model.

Reference	Location	Planting Date	Physiological Maturity Date
Jones and Popham 1997	Bushland	Late September, Early October	Late June, Early July
Baumhardt and Jones 2002	Bushland	Late September, Early October	Early July
Aiken et al. 2013 Aiken Unpublished	Colby	September 17 to October 20	June 18 to July 3
Schlegel et al. 2002	Tribune	September	Late June, Early July
KSWB	-	September 17	June 22

using a simple least squares regression model. The level of significance was 0.05 and coefficients of determination (R^2) values were calculated to determine how well the linear model fit the data. Root mean square error (RMSE) was calculated to measure the model accuracy. A t-test was calculated to compare slope of the observed CWU-yield relationship with that of the pooled modeled CWU-relationship for each study to determine if the two slopes were significantly different. The following formula from Cohen et al. (2003) was used to calculate the t-value:

$$t = \frac{b_1 - b_2}{\sqrt{s_{b_1}^2 + s_{b_2}^2}}, \qquad df = n_1 + n_2 - 4 \qquad [9]$$

where t is the t-value, b_1 and b_2 are the slopes of the two regression lines, s_{b_1} and s_{b_2} are the standard errors of the two regression lines, df is the degrees of freedom, and n_1 and n_2 are the sample sizes for the two lines. When the observed t-value is greater than a corresponding t-value at the 0.05 significance level, we reject the null hypothesis that there is no difference between the slopes.

Results

This section is divided into two parts: results of the performance measures for winter wheat and those of grain sorghum. In each section are the performance measures for crop water use, yield, and the yield-crop water use relationship, comparing observed and modeled results.

Winter Wheat

Simulation results were compared against field observations of water use and yield for each set of field studies. Regressing modeled wheat crop water use with observed yields (Fig. 2, Table 4) resulted in a linear relationship in four of the five cases (Aiken Unpublished, Jones and Popham 1997, Baumhardt and Jones 2002, and Schlegel et al. 2002), as well as the two cases of pooled results (one case with all the data and one case with all data except Jones and Popham (1997)). The KSWB model had satisfactory predictive skill for the Baumhardt and Jones (2002) and Schlegel et al. (2002) observations using the Nash-Sutcliffe method, meaning they had a NS coefficient greater than 0.5. The KSWB model had more predictive skill than the mean for both sets of pooled results. In two of the five cases (Jones and Popham 1997, and Schlegel et al. 2002), and both sets of pooled results, predictive accuracy had a negative bias in slope (indicated by slopes significantly different from one) which was offset by a positive bias in intercept (indicated by intercept significantly different from zero). Predicted crop water use was generally equal to or greater than observed water use. Predictive accuracy (RMSE = 57.3 mm, restricted pooled results) declined when the Jones and Popham (1997) study was included in pooled results.

Modeled wheat yields regressed on observed yields (Fig. 3, Table 5) resulted in a linear relationship in one of five cases, as well as for the pooled results of all cases. The predicted yields in this case, as well as the pooled results, exhibited negative bias in slope and offsetting positive bias in intercept. The KSWB model demonstrated more predictive skill than the mean for wheat yields reported in Schlegel et al. (2002) and Aiken et al. (2013), as well as both sets of pooled results. Predictive accuracy (excluding Jones and Popham 1997) was 0.90 Mg ha^{-1}.

Observed yield thresholds for the yield-crop water use relationship for wheat (Table 6) ranged between 129 and 218 mm (excluding the Jones and Popham (1997) case, with an unrealistic negative value for yield threshold). Corresponding observed slopes of the relationship were between 8.6 and 19.6 kg ha^{-1} mm^{-1}. Three of the five cases and both of the pooled cases were found to be linear. No differences were detected between observed slopes and slope of the restricted pooled results for four of the five cases. The modeled yield threshold was numerically greater than the observed yield threshold. Figure 4 presents crop yield (Mg/ha) in relation to crop water use (mm) for winter wheat; the solid black line represents pooled modeled yield regressed on pooled modeled water use (all studies), the symbols represent observed yield and crop water use, and the dashed lines represent regression of observed yield regressed on observed water use.

The modeled yield thresholds for the yield-crop water use relationship for wheat (Table 7) ranged between 171 and 304 mm. Modeled slopes of the same relationship ranged between 9.95 and 19.60 kg ha^{-1} mm^{-1}. All cases were found to be linear.

Grain Sorghum

In two of the five cases of sorghum crop water use, as well as the pooled results, there was a linear relationship (Aiken Unpublished, and Baumhardt and Jones 2002 with Moroke et al. 2011) when the modeled values were regressed on observed values (Fig. 5, Table 8). The model had satisfactory predictive skill in one of these cases, and greater skill than the mean value for the other case as well as in both sets of the pooled results. No bias was detected in one linear case; a negative bias in slope was observed in the other linear case. Pooled results exhibited offsetting negative bias in slope and positive bias in intercept.

For modeled sorghum yields regressed on observed yields (Fig. 6, Table 9), two of five cases (Jones and Popham 1997, and Schlegel et al. 2002) and both sets of pooled results exhibited a linear relationship. A negative bias in slope was offset by a positive bias in intercept for this case and both pooled results. The KSWB model demonstrated more predictive skill than the mean for one case (Aiken et al. 2013), as well as the restricted pooled results. Three of the five cases and one of the pooled

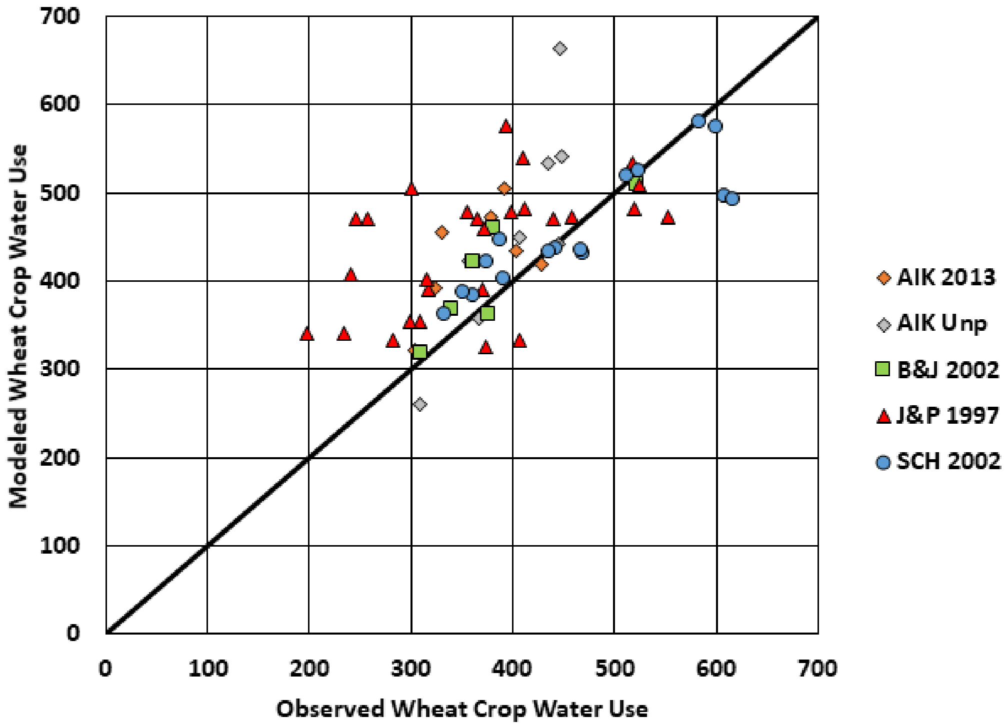

Figure 2. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop water use (mm) is presented in relation to field observations of water use for winter wheat; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 4. Regression performance between modeled and observed crop water use for wheat.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.734	160	0.328	0.1793‡	53.4	-2.32
AIK Unp	8	2.01	-349	0.730	0.0069	68.9	-2.88
B&J 2002	6	0.826	90.7	0.739	0.0281	40.3	0.598
J&P 1997	27	0.398*	293†	0.228	0.0047	62.7	-0.382
SCH 2002	16	0.595*	180†	0.771	<0.0001	32.8	0.720
Pooled	64	0.499*	244†	0.375	<0.0001	61.0	0.103
Pooled – No J&P 1997	37	0.659*	167†	0.505	<0.0001	57.3	0.378

* Slope different from one at a significance level of 0.05.

† Intercept different from zero at a significance level of 0.05.

‡ Did not pass the test for linearity (from p-value).

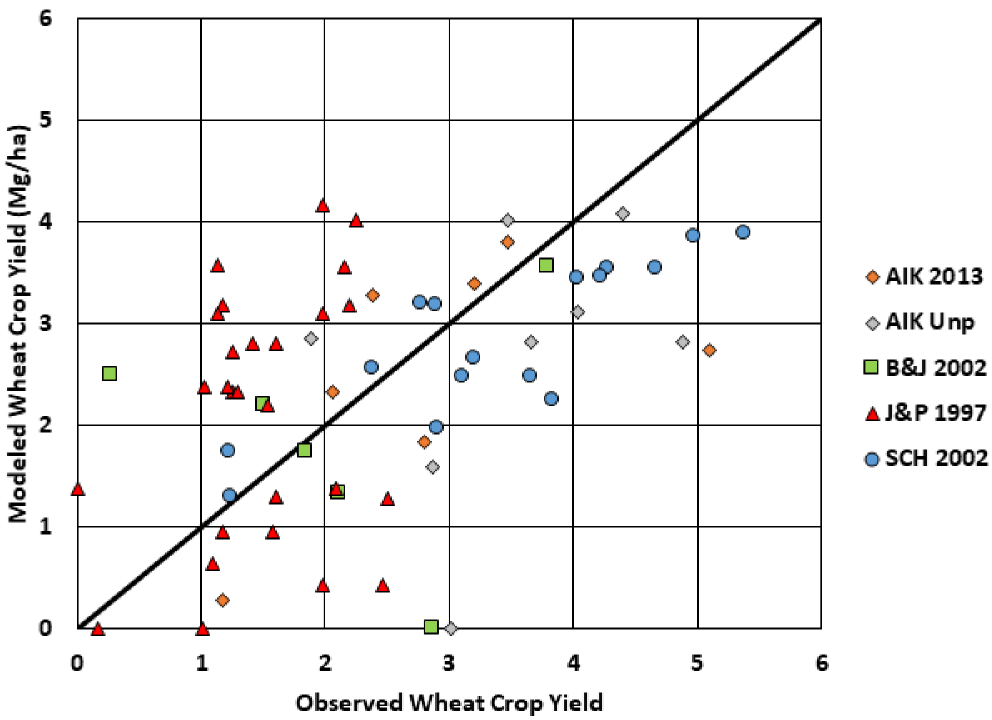

Figure 3. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop yield (Mg/ha) is presented in relation to field observations of crop yield for winter wheat; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 5. Regression performance between modeled and observed yields for wheat.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.559	0.915	0.337	0.1715‡	1.06	0.0946
AIK Unp	8	0.535	0.777	0.146	0.3508‡	1.33	-1.84
B&J 2002	6	0.0159	1.86	0.000255	0.9760‡	1.34	-0.989
J&P 1997	27	0.501	1.35†	0.0624	0.209‡	1.22	-4.02
SCH 2002	16	0.552*	0.960†	0.717	<0.0001	0.430	0.432
Pooled	64	0.417*	1.37†	0.217	0.00011	1.04	0.0298
Pooled – No J&P 1997	37	0.491*	1.06†	0.316	0.00030	0.898	0.0242

* Slope different from one at a significance level of 0.05.
† Intercept different from zero at a significance level of 0.05.
‡ Did not pass the test for linearity (from p-value).

Table 6. Regression performance between observed yields and observed crop water use for wheat.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	19.6	-4280	0.538	0.0606†	0.921	218
AIK Unp	8	14.0	-2080	0.590	0.0260	0.655	149
B&J 2002	6	8.58	-1210	0.276	0.2843†	1.140	141
J&P 1997	27	3.08*	365	0.230	0.0114	0.552	-118
SCH 2002	16	10.2	-1310	0.686	<0.0001	0.695	129
Pooled	64	8.71	-1020	0.399	<0.0001	1.010	117
Pooled – No J&P 1997	37	10.0	-1090	0.503	<0.0001	0.876	109

Note: n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

* Differed significantly from the pooled modeled regression.

† Did not pass the test for linearity (from p-value).

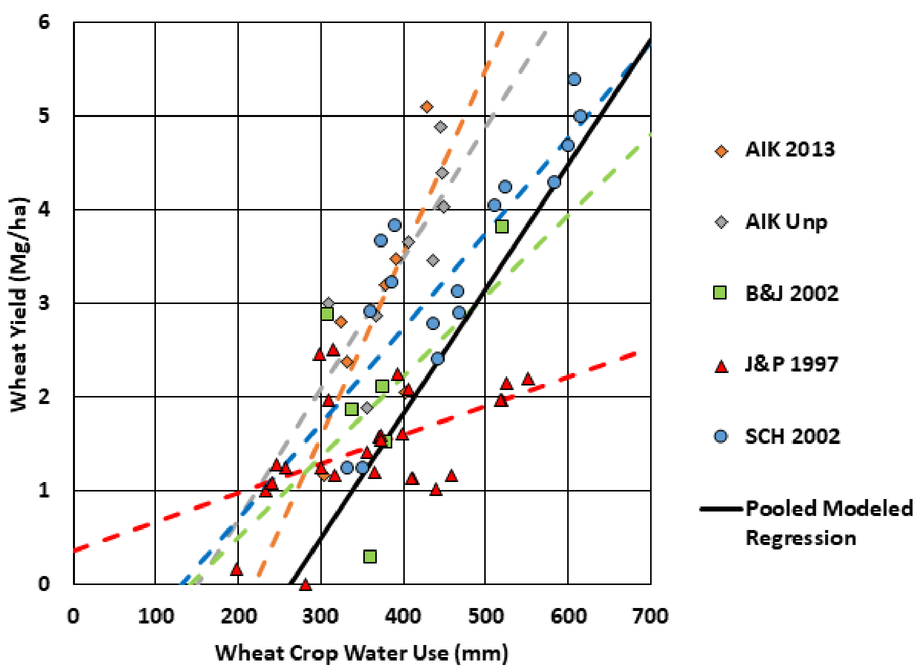

Figure 4. Crop yield (Mg/ha) is presented in relation to crop water use (mm) for winter wheat; the solid black line represents modeled yields from all studies regressed on modeled water use, the symbols represent observed yield and crop water use, and the dashed lines represent observed yield regressed on observed water use. Studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 7. Regression performance between modeled yields and modeled crop water use for wheat.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	19.6	-5860	0.956	0.0001	0.274	299
AIK Unp	8	9.99	-1920	0.850	0.0011	0.556	192
B&J 2002	6	15.8	-4540	0.872	0.0064	0.478	287
J&P 1997	27	15.6	-4740	0.832	<0.0001	0.518	304
SCH 2002	16	9.95	-1700	0.712	<0.0001	0.434	171
Pooled	64	13.3	-3500	0.770	<0.0001	0.561	263
Pooled – No J&P 1997	37	11.8	-2660	0.788	<0.0001	0.500	225

cases had slopes that were not different from one, and three of the five cases and none of the pooled cases had intercepts that were not different from zero at a significance level of 0.05.

Observed yield thresholds for the yield-crop water use relationship for sorghum (Fig. 7, Table 10) ranged between 89 and 275 mm, excluding the case of Jones and Popham (1997). Corresponding slopes ranged from 13.8 to 39.5 kg ha^{-1} mm^{-1}. Three of the five cases and both of the pooled cases were found to be linear. Three of the cases, Aiken (Unpublished), Jones and Popham (1997), and Baumhardt and Jones (2002) with Moroke et al. (2011), had slopes that differed from that of the pooled modeled regression. Figure 7 presents crop yield (Mg/ha) in relation to crop water use (mm) for grain sorghum; the solid black line represents pooled modeled yield regressed on pooled modeled water use (results from all studies), the symbols represent observed yield and crop water use, and the dashed lines represent regression of observed yield regressed on observed water use.

The modeled yield thresholds for the yield-crop water use relationship for sorghum (Fig. 7, Table 11) ranged between 191 and 213 mm. The modeled slopes were very similar as well, ranging between 25.9 and 32.0 kg ha^{-1} mm^{-1}. All cases were found to be linear.

For both wheat and grain sorghum, the precision of the yield-water use relationship was greater for modeled results (RMSE = 0.50 and 0.52 kg ha^{-1} mm^{-1}, respectively) than the relationship derived from observations (RMSE = 0.88 and 1.62 kg ha^{-1} mm^{-1}, respectively).

Discussion

Analysis of pooled results are differentiated with respect to the Jones and Popham (1997) study; either excluding or including the results of this 10-yr field study. Review of predictive accuracy for individual studies and pooled studies support this approach. Results of the earlier Bushland, TX study (Jones and Popham 1997) appear to differ from the later Bushland study (Baumhardt and Jones 2002), especially in slopes and yield thresholds of the yield-water use relationship for both wheat and sorghum. The later study had greater slopes and yield thresholds than the earlier study in both crops, based on experimental results. In contrast, the modeled results were very similar for the two studies, indicating similarity of conditions considered by the model. Nielsen and Vigil (2017) reported a range of slopes for grain sorghum water productivity (11.1 to 34.4 kg ha^{-1} mm^{-1}) from studies conducted in Bushland, TX, attributing this

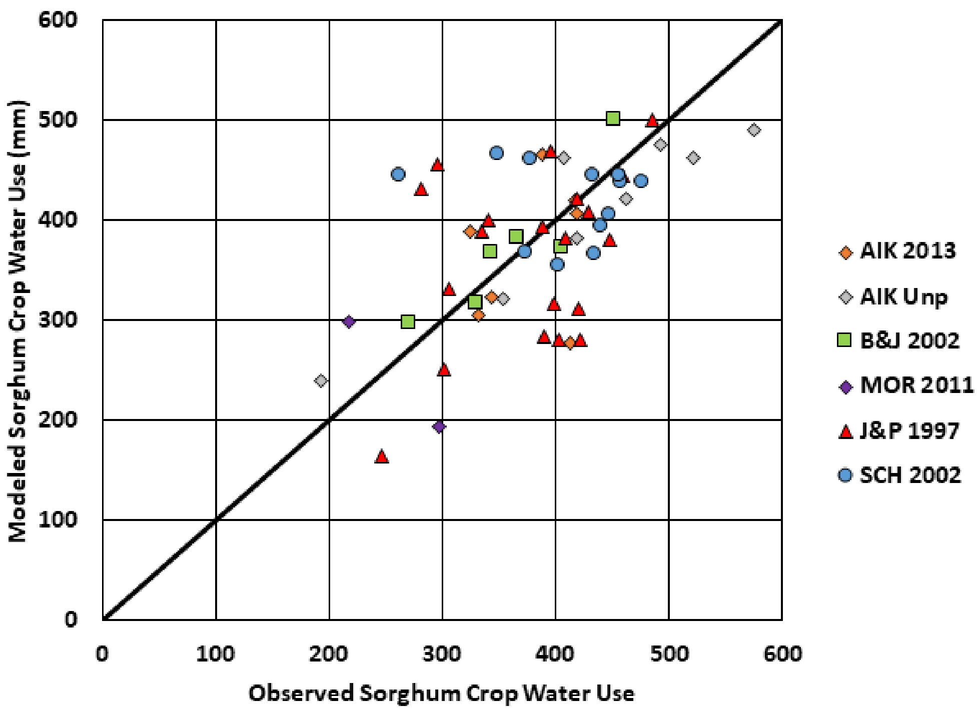

Figure 5. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop water use (mm) is presented in relation to field observations of water use for grain sorghum; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 8. Regression performance between modeled and observed crop water use for grain sorghum.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.448	201	0.0761	0.5493‡	72.2	-1.77
AIK Unp	8	0.688*	112	0.857	0.0010	35.8	0.787
B&J 2002 and MOR 2011	8	0.915	33.9	0.603	0.0234	59.9	0.435
J&P 1997	20	0.496	177	0.147	0.0950‡	80.3	-0.725
SCH 2002	12	-0.109*	463.2†	0.0282	0.6020‡	40.6	-0.662
Pooled	55	0.584*	154†	0.322	<0.0001	65.0	0.101
Pooled – No J&P 1997	35	0.605*	152†	0.446	<0.0001	56.0	0.389

* Slope different from one at a significance level of 0.05.

† Intercept different from zero at a significance level of 0.05.

‡ Did not pass the test for linearity (from p-value).

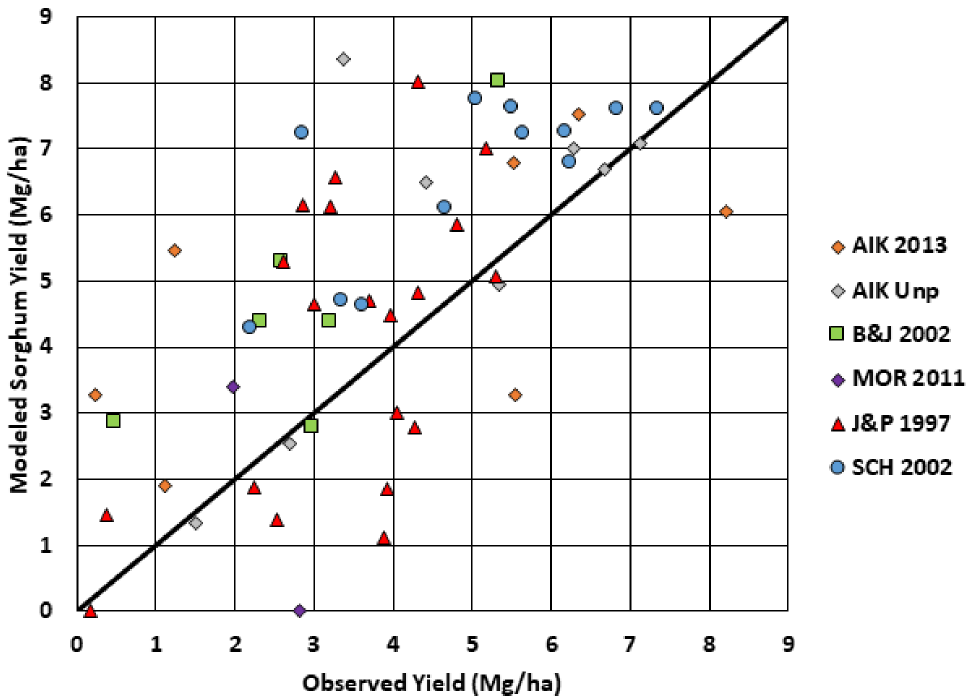

Figure 6. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop yield (Mg/ha) is presented in relation to field observations of crop yield for grain sorghum; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 9. Regression performance between modeled and observed yields for grain sorghum.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.423*	3.19†	0.396	0.1301‡	1.78	0.304
AIK Unp	8	0.814	1.76	0.456	0.0663‡	1.95	-0.0437
B&J 2002 and MOR 2011	8	0.980	1.23	0.336	0.1319‡	2.03	-1.74
J&P 1997	20	0.932	0.946	0.311	0.0106	1.94	-1.22
SCH 2002	12	0.582*	3.68†	0.538	0.0066	0.930	-0.510
Pooled	55	0.770	1.92†	0.423	<0.0001	1.74	-0.148
Pooled – No J&P 1997	35	0.690*	2.49†	0.464	<0.0001	1.62	0.0329

* Slope different from one at a significance level of 0.05.

† Intercept different from zero at a significance level of 0.05.

‡ Did not pass the test for linearity (from p-value).

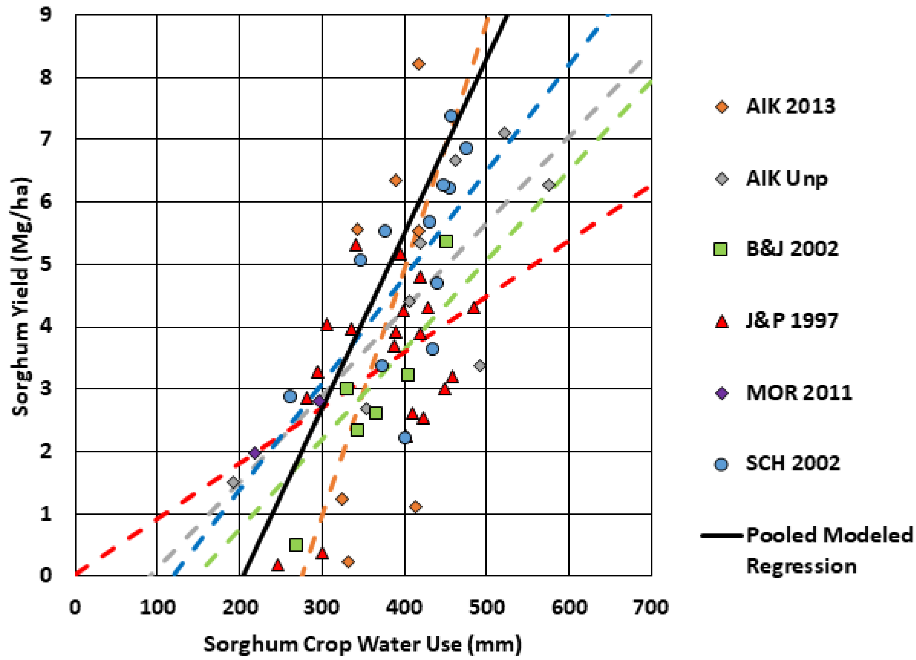

Figure 7. Crop yield (Mg/ha) is presented in relation to crop water use (mm) for grain sorghum; the solid black line represents modeled yields from all studies regressed on modeled water use, the symbols represent observed yield and crop water use, and the dashed lines represent observed yield regressed on observed water use. Studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 10. Regression performance between observed yields and observed crop water use for grain sorghum.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	39.5	-10800	0.287	0.2155†	2.88	275
AIK Unp	8	13.8*	-1230	0.645	0.0164	1.30	89.4
B&J 2002 and MOR 2011	8	14.4*	-2110	0.618	0.0206	0.910	147
J&P 1997	20	8.91*	25.6	0.184	0.0594†	1.26	-2.88
SCH 2002	12	17.0	-2010	0.392	0.0294	1.34	118
Pooled	55	15.5	-2090	0.377	<0.0001	1.53	135
Pooled – No J&P 1997	35	17.5	-2640	0.447	<0.0001	1.62	151

Note: n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

* Differed significantly from the pooled modeled regression.

† Did not pass the test for linearity (from p-value).

Table 11. Regression performance between modeled yields and modeled crop water use for grain sorghum. Performance measures for modeled sorghum yields regressed on modeled sorghum crop water use.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	30.3	-6300	0.984	<0.0001	0.287	208
AIK Unp	8	26.8	-5350	0.927	0.0001	0.713	200
B&J 2002 and MOR 2011	8	25.9	-5700	0.977	<0.0001	0.379	191
J&P 1997	20	26.1	-5410	0.944	<0.0001	0.553	207
SCH 2002	12	32.0	-6830	0.927	<0.0001	0.369	213
Pooled	55	28.0	-5720	0.929	<0.0001	0.612	204
Pooled – No J&P 1997	35	28.5	-5670	0.944	<0.0001	0.520	199

Note: n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

variability to differences in evaporative demand, timing of water stress, crop residue management, and soil fertility. The combined grain sorghum results of Baumhardt and Jones (2002) and Moroke et al. (2011) indicate a crop water productivity value (14.4 kg ha^{-1} mm^{-1}) within this range.

The KSWB model had similar predictive accuracy for crop water use of wheat and grain sorghum, considering RMSE, Nash-Sutcliffe, and the coefficient of determination for the restricted pooled results. Furthermore, the predictive accuracy for yield was similar for both crops, though accuracy was substantially reduced and the Nash-Sutcliffe criteria for predictive skill was not met. Therefore, it is remarkable to observe the performance of the KSWB model in replicating the yield-water use relationship for both wheat and grain sorghum.

The relationship of wheat yield to water use simulated by the model was similar to the relationships developed in four of the five field studies. Both the slopes and yield thresholds for the five cases analyzed for this study were similar to those reported in Mathews and Brown (1938) and Aiken et al. (2013), with the exception of Jones and Popham (1997). However, the magnitude of the yield thresholds in each of the five studies was numerically less than that derived from the pooled simulated results, indicating that yield response to water use began with less water than calculated by the model. This suggests the KSWB model systematically underestimates wheat productivity in response to water use.

In contrast, the sorghum yield response to water use relationship simulated by the KSWB model (28.0 kg ha^{-1} mm^{-1}, pooled modeled regression, Table 11) differed from that of three studies (Aiken Unpublished, Jones and Popham 1997, and Baumhardt and Jones 2002 with Moroke et al. 2011, Table 10) – particularly the slope of the yield response to an increment of water use. Simulated sorghum yield thresholds (191 – 213 mm, Table 11) were consistent with observed yield thresholds for four of the five locations (89 – 275 mm, Table 10). Experimental yield response to an increment of water use was substantially less (approximately half) than calculated by the KSWB model (28.0 kg ha^{-1} mm^{-1}, pooled modeled regression, Table 11) for four of the five studies (8.9 – 17.0 kg ha^{-1} mm^{-1}, Table 10). This result indicates that the model predicted a much higher yield response to water than was observed and a substantial gap between actual and potential sorghum yields.

Regional trends

Most of the slopes of the yield to water use relationship (derived from field observations) were smaller in Bushland, TX than in Tribune or Colby, KS for both wheat and sorghum. One possible reason for this is that Bushland has higher temperatures, on average. Growing seasons with higher temperatures can decrease crop yields and decrease the slope of the yield-water use relationship because of the heat stress. Increased evaporative demand in Bushland could also contribute to this apparent regional trend of decreased crop water productivity at the lower latitude.

Uncertainty in planting date likely contributes to the apparent lack of predictive skill in the KSWB model. Though this model uses constant planting dates and subsequent crop development dates for wheat and grain sorghum, the start and end dates for the crop seasons at each of the sites are not the same day as indicated by the date range given in Table 2. Factors such as timing of precipitation influence when planting begins. For example, in Bushland the planting dates for wheat could be anywhere between late September and late October, but for Colby the planting date could be as late as October 20th. For sorghum, harvest dates could be as early as September 20th (Colby) or as late as early November (Bushland). This contributes to uncertainty associated with model output, because if the model has a shorter growing season than the study, the precipitation simulated during the growing season will likely differ from the field conditions. For example, large precipitation events that occur after the end of the simulated growing season but before the end of the observed growing season could introduce substantial discrepancies in simulated and observed water use, which are independent of the model's predictive skill. Apparent differences between simulated and observed crop water use and yield formation could be affected by regional differences in planting date and crop development, which are not represented with the constant planting dates used in the implementation of the KSWB model.

Most of the modeled points used to define the yield to water use relationship fall on the same line and have very small dispersion, especially for sorghum, but also for wheat. The yield formation algorithm calculates yield as a weighted average of crop water use with stress factors comprising the weighting factors. If there is no stress, weighting factors will have no effect, and yield-water use relationship will be a straight line. The smaller coefficient of determination for the simulated yield-water use relationship for wheat suggests a greater role of stress factors in wheat yield calculation. The dispersion of observed data points about the yield-water use relationships of wheat and sorghum are substantially greater than for the modeled relationship, as indicated by the smaller coefficient of determination for the observed relationship. This suggests that factors other than water may be limiting yield responses. The model accounts for some of the stress factors such as water and temperature effects on evaporative demand, but there are many factors other than these that influence yields. Weeds, pests, diseases, tillage, fertility, hail, and management practices could all be potential factors limiting yields in the experimental results. These factors are beyond the scope of the KSWB model. One of the sources of uncertainty in the model is that the actual planting and physiological maturity dates for each of the field studies differ from the model assumptions. Other factors include the uncertainty of hydraulic properties and that the soil profile was treated as a block of homogenous soil instead of being broken up into layers, each with different properties.

While this study analyzed a number of different cropping sequences of wheat and sorghum, these sequences were not compared with each other. Although this analysis could be useful, it was not undertaken in this work. For example, Aiken et al. (2013) found that replacing an uncropped fallow period with an oilseed crop could reduce grain yield response of continuous wheat by 31%. A study done by Mohammad et al. (2012) found that wheat grain yield was significantly greater in wheat-summer legume-wheat and wheat-fallow-wheat than in a wheat-summer cereal-wheat rotation. Peterson et al. (1996) found that the most direct and practical solution to improve the efficient use of precipitation may be to include a summer crop following winter wheat that would make better use of summer precipitation than the use of a fallow period.

Conclusion

The KSWB model demonstrated predictive skill for crop water use, but not for grain sorghum and winter wheat yield. The simulated yield-water use relationship was consistent with that of four of five field studies of wheat and two of five field studies of sorghum. Simulated yield response of wheat to water use indicated the actual yield threshold of water use may be smaller than simulated, but observed yield response to subsequent water use was similar to that which was simulated. In contrast, the simulated yield threshold for grain sorghum appeared similar to the measured value, but observed yield response to subsequent water use was approximately half the potential value identified by the KSWB simulation on one of the field studies reported here. The KSWB model provides a useful analytic framework for quantifying water supply constraints to grain productivity.

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Calibration and Validation of CSM-CROPGRO-Cotton Model Using Lysimeter Data in the Texas High Plains

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Abstract: Texas High Plains (THP), one of the most important food and fiber producing regions in the Ogallala Aquifer Region, currently faces rapid decline of groundwater levels. Predicted climate extremes and high temporal variability in growing season precipitation may require growers to pump more groundwater from the Ogallala Aquifer to meet higher crop water demand. The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) is a widely used crop simulation tool for evaluating impacts of different water and crop management practices, including irrigation on crop yield and water use efficiency. In this study, CROPGRO-Cotton module of the DSSAT was calibrated and validated using 2000, 2001, 2002, and 2010 irrigated lysimeter field data managed by the USDA-ARS (United States Department of Agriculture - Agricultural Research Service) Conservation and Production Research Laboratory at Bushland, TX. The lysimeter field consisted of four equal plots designated as NE, SE, NW, and SW. Crop growth characteristics including leaf area index (LAI), above ground biomass (AGB), evapotranspiration (ET), soil moisture, and lint yield of 2000-NE, 2000-SE, and 2001-NE, were used for calibration and 2002-NE, 2010-NE, and 2010-SE were used for validation. The calibrated and validated model was used to simulate the long term (1924-2012) crop yield and seasonal crop ET. During the calibration process, some of the cultivar and ecotype parameters that influence LAI, AGB, and lint yield were adjusted for better statistical results. Measured and simulated LAI, AGB, ET, soil moisture, and lint yield showed good agreement during calibration and validation as indicated by performance statistics such as r^2 from 0.70 to 0.82, and percent error (PE) = -0.85 to 17.3% for LAI; r^2 = 0.89 to 0.95, and *PE* = -7.36 to -13.66% for AGB; and r^2= 0.90 to 0.94, and PE = 3.20 to 3.44% for ET during calibration and validation, respectively. The model underestimated ET during peak vegetative growth and development stage except in some circumstances. The calibrated and validated model was able to simulate lint yield and seasonal ET during a long term (1924-2012) historic period for Bushland, TX, under irrigated conditions. The calibrated model could be used to schedule ET based irrigation management practices in the THP and to estimate future ET for other modeling experiments.

Keywords: *crop model, DSSAT, above ground biomass, leaf area index, soil moisture, evapotranspiration, Ogallala Aquifer, cropping system model*

Cotton (*Gossypium hissutum* L.) is one of the most important fiber crops for the textile industry and also provides seed for animal and oil industries. Among several major cotton producing countries, USA is the leading exporter of cotton. Texas High Plains (THP) is one of the major cotton producing regions of the U.S., contributing about 25% of total U.S. cotton production (USDA 2012). About 95% of the water used for irrigation in the THP is pumped from the Ogallala Aquifer, one of the largest freshwater aquifers in the world (HDR 2001). Due to excessive groundwater pumping for irrigation, annual withdrawal has outpaced natural recharge, resulting in large declines in the amount of water available for irrigation and increased groundwater pumping costs (Nieswiadomy 1985; Musick et al. 1988; Colaizzi et al. 2009; Adusumilli et al. 2011). Numerous researchers (Scanlon et al. 2002; Sophocleous 2010; Haacker et al. 2016) have reported that ongoing depletion of the Ogallala Aquifer poses major challenges for crop production in the THP. In addition, researchers (Adams et al. 1998; Adhikari et al. 2016) also predict future reduced precipitation and warmer summer temperatures in the THP. It is expected in the coming decades that there will be a gradual shift in cotton production from irrigated to dryland/rainfed management. Therefore, the development and implementation of better irrigation management practices based on a critical understanding of the interaction among soil processes, weather variables, and crop management practices is necessary.

The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) is a widely used tool and is capable of simulating crop growth stage, development, and yield in response to the variability in agrometeorological conditions, soil properties, and management practices (Thorp et al. 2008; Hoogenboom et al. 2012). Using the field experimental data, a well calibrated DSSAT-CSM model could successfully be used to simulate crop response under various sets of experimental conditions, which can ultimately speed decision making by reducing the time and resources required for long term field experimentation. Numerous researchers (Rezzoug et al. 2008; Liu et al. 2011; Hoogenboom et al. 2012; Wajid et al. 2014; Kisekka et al. 2015; Adhikari et al. 2016; Attia et al. 2016, Mauget et al., 2017) have used DSSAT-CSM for different applications. Wajid et al. (2014) used the CSM-CROPGRO model to simulate development, growth, and seed cotton yield of four cotton cultivars under varying nitrogen fertilizer rates and planting dates in Pakistan. They reported that the simulated crop phenology, seed cotton yield, and total dry matter were reasonable when compared with the observed data. The CSM-CROPGRO-Cotton model was used to study the impact of El Niño Southern Oscillation (ENSO) based climate variability on crop water use efficiency across Alabama, Florida, and Georgia (Garcia y Garcia et al. 2010). The CSM-CROPGRO model combined with kriging was used by Guerra et al. (2007) to estimate the spatial distribution of monthly irrigation water use for cotton. Similarly, Ortiz et al. (2009) used the CROPGRO-Cotton model to study the impact of root-knot nematodes on cotton biomass in Tifton, Georgia; Cammarano et al. (2012) used CROPGRO-Cotton to evaluate the economics of cotton irrigation strategies in Australia; and Zamora et al. (2009) used CROPGRO to simulate cotton production under different light levels in a pecan alley cropping system in Jay, Florida. Recently, Modala et al. (2015) evaluated the CSM-CROPGRO model for the Texas Rolling Plains using the field experimental data on different levels of irrigation at different stages of cotton growth and used the calibrated model to identify and evaluate optimum deficit irrigation strategies for the region. Similarly, Adhikari et al. (2017) used the CROPGRO-Cotton model to access the impacts of winter wheat cover crops on the cotton production system of the Texas Rolling Plains. In the semi-arid climate of Southern Kansas, Araya et al. (2017) evaluated DSSAT-CSM for different crops such as corn, wheat, and grain sorghum for water limited cropping systems. They reported that the model was able to adequately simulate the onset of crop phonological stages such as flowering, maturity, crop yield, and above ground biomass (AGB) for these three crops. DSSAT-CSM was also used to study the impact of climate variability on various soil organic carbon and carbon mediated processes (Porter et al. 2010). Reddy et al. (2002) used the cotton simulation model GOSSYM to understand the implication of climate change on cotton production at Stoneville, Mississippi, USA. Most of these studies used field experimental data for only one or two crop growing seasons to calibrate and validate the DSSAT-CSM model. It is reported that using long term measured data and including calibration of the model for sensitive crop characteristics will not only enhance confidence in the model but also allow the user to evaluate crop and water management strategies under a wide range of climatic conditions. The current study used 2000, 2001, 2002, and 2010 cotton growing season data from large lysimeter fields managed by USDA-ARS Conservation and Production Research Laboratory at Bushland, TX. Measured crop characteristics data included leaf area index (LAI), AGB, lint yield, crop evapotranspiration (ET), and soil moisture. Use of crop ET measured during a field lysimeter study for calibration and validation processes increases the value of this study because crop ET is considered one of the most significant components of the hydrological process required for irrigation scheduling. To the best of our knowledge, only the CERES-Maize model (Marek et al. 2017) was calibrated using long term daily and seasonal lysimeter-based ET in the THP. Therefore, the objectives of the study were: 1) to calibrate and validate the CROPGRO-Cotton model using the long term lysimeter data during 2000, 2001, 2002, and 2010 under irrigated (sprinkler irrigation system) conditions, and 2) to use the calibrated CROPGRO-Cotton model to simulate long term (1924-2012) ET and lint yield.

Materials and Methods

Study Site

Measured data for this study during 2000, 2001, 2002, and 2010 cotton growing seasons were obtained from a field experiment conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX (35.19° N, 102.10° W, 1170 m above MSL). Irrigated cotton was planted in the lysimeter study only during these years (2000, 2001, 2002, and 2010). The research area consisted of four, 4.7 ha subdivided fields designated as NE, SE, NW, or SW, each containing a centrally located weighing lysimeter. These fields were irrigated with a N-S oriented, ten-span, 457 m linear-move sprinkler irrigation system travelling E-W or W-E. Crop management data including cotton growth characteristics such as LAI, AGB, lint yield, daily ET, and soil moisture during 2000-NE, 2000-SE, 2001-NE, 2002-NE, 2010-NE, and 2010-SE cotton growing seasons and fields were obtained. Adjacent to the lysimeter fields is a 1,760 m^2 irrigated, mowed grass reference ET weather station, maintained in accordance with the American Society of Civil Engineers (ASCE) - Environmental and Water Resource Institute (EWRI) specifications (Walter et al. 2005). The soil texture in the study site is characterized as deep, well drained Pullman silty clay loam soil (fine, mixed, superactive, thermic Torrertic Paleustoll) (Marek et al. 2016a). Soil data needed for the study were obtained from a recent modeling study conducted at Bushland, TX (Marek et al. 2016a). More detailed descriptions about the soil, the lysimeter field study, and the lysimeter setup can be found elsewhere (Marek et al. 2016a; 2016b). Soil moisture at different depths during different cotton growing seasons was measured using neutron probes. Details on the procedure and measurement of soil moisture using neutron probes in the lysimeter field are provided by Evett et al. (2003) and Evett (2008).

DSSAT-CROPGRO-Cotton Cropping System Model

The CSM-CROPGRO-Cotton model distributed with the DSSAT was calibrated and validated using field measured lysimeter data over a range of cotton growing seasons (2000, 2001, 2002, and 2010). The DSSAT integrates a database management system (soil, climate, and management practices) and crop models with various application programs (Hoogenboom et al. 2012). It brings together 42 individually developed crop models to a single platform. The latest DSSAT 4.6.1.0 version was used in the current study. The CROPGRO-Cotton model predicts cotton growth, LAI, AGB, ET, yield, and soil water content in response to weather, soil type, crop management practices, and crop cultivars. Model default Priestley-Tylor method was used to estimate ET. The model also estimates various crop development stages such as emergence, first leaf, first flower, first seed, first crack boll, and 90% open boll. The CROPGRO-Cotton model requires various soil parameters such as percent sand, clay, stone, organic carbon, pH, cation exchange capacity, slope, albedo, color, drainage, drained upper limit (DUL), lower limit (LL), saturated water content (SAT), hydraulic conductivity, organic carbon content, bulk density, total soil nitrogen, root growth factor (SRGF), and soil fertility factor (SLPF) (Jones et al. 2003). Based on the initial soil moisture provided in the soil file, DSSAT computes daily soil water balances required to simulate soil water content (Ritchie and Otter 1985). Daily soil water balance is calculated using the following equations (Jones et al. 2003; Jiang et al. 2016):

$$\Delta S = I + P - D - R - T - S_{Evap} - ET_{Mulch} \tag{1}$$

where ΔS is change in soil water (mm), I is amount of irrigation (mm), P is precipitation (mm), D is drainage (mm), R is runoff (mm), T is transpiration (mm), S_{Evap} is soil evaporation (mm), and ET_{Mulch} is evaporation from the mulch surface (mm).

Model Input

Crop Management Data. The details of tillage, planting, fertilizer application, harvesting, and irrigation management practices adopted during 2000, 2001, 2002, and 2010 cotton growing seasons are presented in Table 1. Each lysimeter field was prepared with tillage practices that included shredding stalks, reshaping beds with a rolling cultivator, and furrow diking between late March and mid-May of each year. Experienced scientists and support staff were involved in implementing field operations and collecting agronomic practices including planting, tillage, irrigation, fertilization, plant sampling, LAI measurement, and soil water measurement. The Paymaster 2145 cotton seed variety was planted in all years using a John Deere Maxemerge Planter at 4-cm depth. Cotton was harvested during a period between early October and mid November each year.

Climate Data. The DSSAT-CSM requires daily maximum and minimum temperature (˚C), incoming solar radiation (MJ m^{-2} d^{-1}), and precipitation (mm) to simulate crop growth and development. Data on wind speed (m km^{-1}), dew point temperature (˚C), and relative humidity (%) are optional. Daily weather parameters for the current study, including daily maximum and minimum temperature, incoming solar radiation, precipitation, wind speed, and relative humidity (%) during 2000 to 2010, were obtained from the USDA-ARS Soil and Water Management Research Unit (SWMRU), Bushland, TX. Missing weather data were obtained from the Texas High Plains Evapotranspiration Network (TXHPET) (Porter et al. 2005) at Bushland, TX weather station. The QA/QC techniques were applied to weather datasets to ensure valid data following the procedure suggested by Marek et al. (2016a). The DSSAT-CSM weather module was used to arrange all the weather data in the standard format.

Table 1. Selected crop management practices during calibration and validation periods.

Year	Planting Date	Harvest Date	Seed Rate (seed ha^{-1})	Irrigation (mm)	Cultivar	Fertilizer (kg ha^{-1}) N-P-K
-----------------Calibration-----------------						
2000-NE	5/16/2000	10/6/2000	89600	292	PAYM2145	50-75-0
2000-SE	5/16/2000	10/6/2000	95200	519	PAYM2145	50-75-0
2001-NE	5/16/2001	10/3/2001	95200	212	PAYM 2145	50-75-0
------------------Validation------------------						
2002-NE	5/21/2002	11/13/2002	89600	494	PAYM2145	168-50-0
2010-NE	5/26/2010	10/28/2010	91840	290	PAYM 2145	120-40-0
2010-SE	5/26/2010	10/28/2010	91840	275	PAYM 2145	120-40-0

Long term (1924-2012) weather data, including minimum and maximum temperature, precipitation, solar radiation, wind speed, and relative humidity, were compiled from TXHPET, USDA-ARS, and National Climatic Data Center (NCDC) datasets. Solar radiation and relative humidity were available from 1990 onwards only. Daily solar radiation for the period prior to 1990 was estimated from the measured maximum and minimum temperature (Hunt et al. 1998). Relative humidity data collected prior to 1990 and wind speed data collected prior to 1963 used in this study were generated using the weather generator in Soil Water Assessment Tool (SWAT), as a part of another study.

Model Calibration and Validation

Crop management data for cotton growing seasons 2000-NE, 2000-SE, and 2001-NE were used for calibration and data from 2002-NE, 2010-NE, and 2010-SE were used for validation. These specific years and locations were selected because only during these years was irrigated cotton grown in the lysimeter fields. Different projects were created with the available crop management practices (Table 1) such as planting date, seed rate, fertilizer application, irrigation, and harvesting. Simulated plant growth characteristics such as LAI, AGB, onset of cotton phenological stages, crop ET, lint yield, and soil moisture were compared against measured data. Since the DSSAT cultivar database did not include the Paymaster 2145 variety, it was added as a new cultivar in the DSSAT cultivar database and its parameters were populated based on the literature values for the THP (Robertson et al. 2007). Some of the cultivar parameters were later adjusted during model calibration. Several other input parameters that govern the crop growth, development, and yield were adjusted manually to improve the model simulation results. The model evaluation was carried out in six steps. Initially, the simulated dates of various cotton phenological stages were compared with actual dates, followed by LAI, AGB, ET, soil moisture, and finally, lint yield. The effect of each adjusted parameter (or growth stage) was studied by graphically comparing simulated and measured lint yield (time series plots). Performance statistics parameters used in this study were coefficient of determination (r^2) (Legates and McCabe 1999), root mean square error (*RMSE*), index of agreement (*d*) (Willmott et al. 1985), and percent error (*PE*), which were calculated using equations 2, 3, 4, and 5, respectively. The r^2 values range between 0 and 1, with 0 indicating "no fit" and 1 indicating "perfect fit" between the simulated and observed values. The *RMSE* values closer to 0 indicate better agreement between the simulated and observed values. The *d* values range between 0 (no agreement) and 1 (perfect fit). The value of *PE* ranges from -100 to ∞, and absolute *PE* values closer to 0 indicate better agreement.

$$r^2 = \frac{\left(\sum_{i=1}^{N}\left(Yi - \bar{Y}\right)\left(\hat{Y}i - \bar{Y}i\right)\right)^2}{\sum_{i=1}^{N}\left(Yi - \bar{Y}\right)^2 \sum_{i=1}^{N}\left(\hat{Y}i - \bar{Y}i\right)^2} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\hat{Y}i - Yi)^2}{N}} \quad (3)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{N}\left(Y_i - \bar{Y}_i\right)^2}{\sum_{i=1}^{N}\left(\left|\hat{Y}_i - \bar{Y}\right| + \left|Y_i - \bar{Y}\right|\right)^2}\right], 0 \leq d \geq 1 \quad (4)$$

$$PE = \left(\sum_{r=1}^{N}\frac{\hat{Y}i - Yi}{Yi}\right)x100 \quad (5)$$

where Yi = observed value, $\hat{Y}i$ = simulated value, $\bar{Y}i$ = average of simulated value, $\bar{Y}$ = average of observed value, and N = number of observations.

The model calibration effort was carried out until the resultant *RMSE* was low, and r^2 and *d* were higher than 0.80. Twelve cultivar parameters and five ecotype parameters were adjusted until the simulated crop development stages, LAI, AGB, ET, soil moisture, and lint yield matched reasonably well with measured data (Table 2).

Long Term Simulation

Long term (1924-2012) weather data were used to simulate lint yield with the calibrated and validated DSSAT-CROPGRO-Cotton model at Bushland, TX. Long term simulations are important to understanding the changes that occur in the environment, their possible impacts on crop production, and the subsequent implementation of crop management decisions. A common planting

Table 2. Comparison of simulated and generally observed dates of onset of cotton phenological stages.

Crop phenological stage	Observed* (days after planting)	Simulated (days after planting)		
------------------Calibration------------------				
		2000-NE	2001-NE	2000-SE
Emergence	4 – 9	4	4	4
Anthesis	60 – 70	63	63	63
Physiological maturity	130 – 160	135	143	139
------------------Validation------------------				
		2002-NE	2010-NE	2010-SE
Emergence	4 – 9	5	4	4
Anthesis	60 – 70	64	64	68
Physiological maturity	130 – 160	155	146	146

*****Robertson et al. 2007.

date of May 16th was assumed for all historic (1924-2012) simulations. Similar management practices such as tillage, fertilizer application, and seeding rate were used every year throughout the 89 years of simulations. The automatic sprinkler irrigation method was implemented by triggering irrigation when the simulated soil moisture was depleted to 50% of available soil water content, and irrigation continued until the soil profile moisture measured 85% of available soil water capacity. In addition, 89 years of long term, historic (1924-2012) data were divided into dry (0-200 mm), normal (201-400 mm), and wet years (> 400 mm), according to the growing season precipitation.

Results and Discussion

Model Evaluation

The simulated dates of onset of various cotton phenological stages at Bushland, TX, such as emergence, anthesis, and physiological maturity during calibration and validation, are presented in Table 2. During both calibration and validation years, simulated emergence, anthesis, and physiological maturity dates were within the observed range (Robertson et al. 2007). In a recent study, Adhikari et al. (2016) also observed similar range of anthesis and physiological maturity days in the THP. Although the simulated physiological maturity dates varied in different years, they were typically within the observed range. The differences in maturity date might have been due to the differences in planting date, photothermal duration, precipitation, and other weather-related parameters during growing seasons. For instance, maturity days during the 2010 growing season were shorter compared to the 2002 cotton growing season. Shorter duration of physiological maturity during 2010 may be attributed to higher air temperatures and lower precipitation measured during that year. For the years of 2002 and 2010, seasonal (121 Days-Of-Year (DOY) to 273 DOY) average maximum temperature was 31.4 ˚C and 32.1 ˚C, respectively, whereas total seasonal rainfall was 205.5 mm and 184.5 mm, respectively. Similarly, seasonal average minimum temperature was 16.9 ˚C during 2002 and 16.8 ˚C during 2010. Low rainfall and higher average maximum temperature during the 2010 growing season might have led to faster development of cotton with shorter time interval between developmental stages.

The calibrated values of cultivar and ecotype parameters for the study site are shown in Table 3. Since observed data, such as LAI and AGB, were available, the cotton cultivar parameters were adjusted to reasonably estimate LAI and AGB after achieving reasonable prediction of onset of crop phenological stage over the growing seasons. Parameters adjusted for Paymaster 2145 cotton cultivars were comparable to that in the DSSAT cultivar file. The adjusted photothermal duration between first flower and first seed (FL-SD) and photothermal duration between plant emergence and flower appearance (EM-FL) was greater than the previously determined values for 'Deltapine 77' and 'Deltapine 555' cultivars. However, photothermal duration between first flower and first pod (FL-SH) were lower than the previously determined values for 'Deltapine 77' and 'Deltapine 555' cultivars. The parameters of the cotton cultivars, such as FL-SD and FL-SD, were adjusted to accurately simulate the crop yield, and the EM-FL parameter, important for accurately predicting the onset of flowering, was tested within a range of 34-48 photothermal days and a value of 41 photothermal days, at which the model simulated reasonable flowering dates, was selected. Previously reported, calibrated values of EM-FL varied between 45 and 51 days, depending on geographical locations and crop management practices. A modeling study conducted by Ortiz et al. (2009) at Tifton, GA, reported an EM-FL value of 45 photothermal days for Deltapine 485/BG/RR cotton cultivar. Similarly, Thorp et al. (2014) obtained calibrated EM-FL values that ranged between 46 and 51 for cotton at Maricopa, AZ. The differences in EM-FL value obtained in this study, when compared to previous studies, might have been due to the differences in weather conditions as well as crop management practices. Cultivar parameters were adjusted as needed; SD-PM was adjusted to 40 photothermal days to simulate the crop harvesting date accurately, and FL-LF was adjusted to 55 days to correctly simulate the end of leaf growth (Table 3). Other cultivar parameters that influence photosynthesis rate, transpiration, and assimilation of carbon in the cotton plant included maximum leaf photosynthesis rate (LFMAX), specific leaf area (SLAVR), and maximum size of full leaf (SIZLF). During the final stage, cultivar parameters such as maximum fraction of daily growth that is partitioned to seed + shell (XFRT), seed filling duration for pod cohort (SFDUR), time required to reach final pod load (PODUR), and threshing percentage (THRSH) were adjusted for obtaining a better comparison between measured and simulated lint yield (Table 3). The ecotype parameters adjusted included relative width of the ecotype in comparison to the standard width per node (RWDTH), adjusted to correctly simulate canopy width, relative height of the ecotype in comparison to the standard height per node (RHGHT), adjusted for canopy height, and FL-VS, adjusted for cessation of stem elongation.

Leaf Area Index (LAI) and Above Ground Biomass (AGB)

The CSM-CROPGRO-Cotton model predicted LAI well during calibration, as indicated by good agreement between measured and simulated LAI (Fig.1a-c) and good model performance statistics (Table 4). The performance statistics indicated that r^2 was 0.70, *d* was 0.87, and *PE* was 17.3% for calibration. The model overpredicted LAI between 189 DOY and 214 DOY, and underpredicted between 214 DOY and ~250 DOY (Fig. 1a & c) during 2000-NE and 2000-SE calibration years. However, during 2001-NE calibration year the model overpredicted LAI between 183 DOY and ~200 DOY and underpredicted between ~201 DOY and 247 DOY (Fig. 1b). Thorp et al. (2014) also reported mixed underpredicted and overpredicted LAI with the CROPGROP-Cotton model when comparing data measured at University of Arizona, Maricopa Agricultural Center, during a 1990 free-air carbon dioxide enrichment (FACE) experiment, due to the differences in the ambient atmospheric CO_2 during the cotton growing seasons. Similarly, underestimated LAI was reported by Ortiz et al. (2009) in their study to simulate growth and yield of cotton plants infected with root knot nematodes using the CROPGRO-Cotton model.

Simulated LAI matched very well with measured LAI (Fig. 2a-c) during validation years. The performance statistics indicated that r^2 was 0.82, *d* was 0.91, and *PE* was 0.85%. Similar to the calibration, the model overestimated LAI

Table 3. Parameters adjusted during the CROPGRO-Cotton module calibration.

Cultivar parameters		**Testing range**	**Calibrated value**
EM-FL	Time between plant emergence and flower appearance (photothermal days)	34-48	41
FL-SH	Time between first flower and first pod (photothermal days)	1-12	3
FL-SD	Time between first flower and first seed (photothermal days)	3-18	5
SD-PM	Time between first seed and physiological maturity (photothermal days)	32-50	40
FL-LF	Time between first flower and end of leaf expansion (photothermal days)	45-75	55
LFMAX	Maximum leaf photosynthesis rate at 30 ºC, 350 ppm CO2, and high light (mg CO2 m-2 s-1)	0.2-2	1.0
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm2 g-1)	110-200	170
SIZLF	Maximum size of full leaf (three leaflets) (cm2)	100-350	250
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.3-1	0.70
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	15-45	35
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	4-16	8
THRSH	Threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity	40-75	60
Ecotype parameters		**Testing range**	**Calibrated value**
PL-EM	Time between planting and emergence (thermal days)	1-5	2
EM-V1	Time required from emergence to first true leaf (thermal days)	2-6	4
RWDTH	Relative width of the ecotype in comparison to the standard width per node	0.8-1.0	0.95
RHGHT	Relative height of the ecotype in comparison to the standard height per node	0.8-1.5	1
FL-VS	Time from first flower to last leaf on main stem (photothermal days)	30-75	40

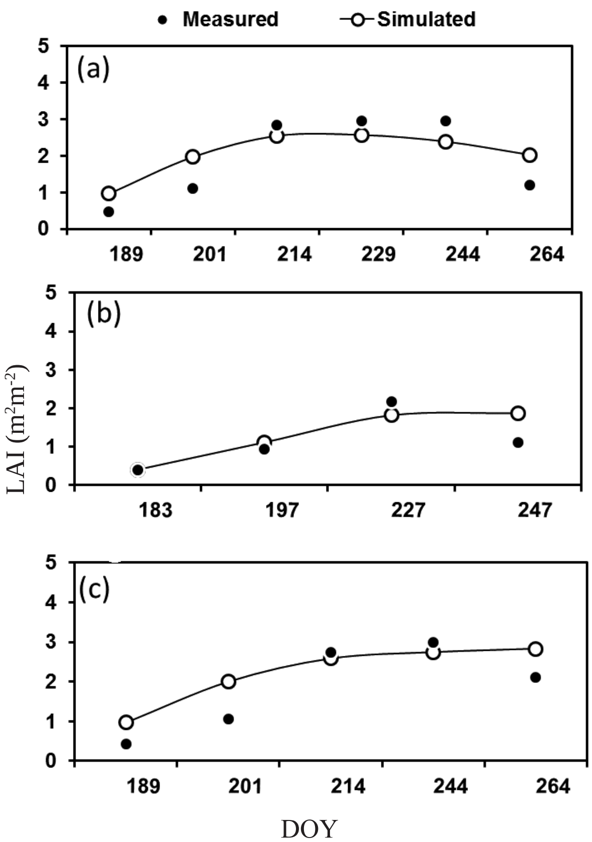


Figure 1. Comparison between measured and simulated leaf area index (LAI) of cotton during different calibration years (a) 2000-NE, (b) 2001-NE, and (c) 2000-SE.

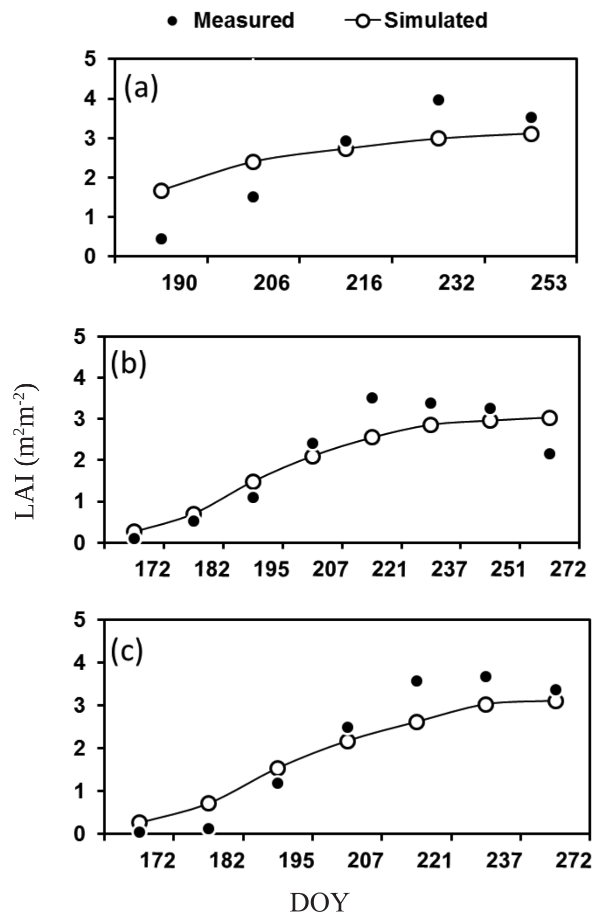


Figure 2. Comparison between measured and simulated leaf area index (LAI) of cotton during different validation years (a) 2002-NE, (b) 2010-NE, and (c) 2010-SE.

between 190 DOY and 216 DOY during 2002-NE validation year, and 172 DOY and 207 DOY during 2010-NE and 2010-SE validation years, considered to be the vegetative growth and development stage. However, the model underestimated LAI between 216 DOY and 253 DOY during 2002-NE; between 207 DOY and 237 DOY (Fig. 2b-c) is considered to be maturity stage. The average measured LAI was 2.98 m^2 m^{-2} during calibration and 2.20 m^2 m^{-2} during validation, whereas simulated LAI was 2.83 m^2 m^{-2} and 2.12 m^2 m^{-2}, respectively.

Similar to LAI, the CSM-CROPGRO-Cotton model predicated AGB very well during both calibration and validation periods (Figs. 3 & 4). The performance statistics during calibration and validation periods are presented in Table 4. During 2000-NE calibration year (Fig. 3a) the model slightly overestimated AGB during early vegetative growth and development stage to maturity and underestimated during senescence, which was in accordance with the LAI. The model estimated AGB perfectly between 183 DOY and ~210 DOY during 2001-NE, and between 189 DOY and ~210 DOY during 2000-SE calibration years. However, the model overestimated during maturity stage (Fig. 3b-c) on both years. During validation years the model overestimated AGB during early growth and development stage and underestimated during maturity (Fig. 4a-c). Similar to our experiments, Ortiz et al. (2009) reported overestimated AGB during early maturity when using the CROPGRO-Cotton model. The average measured AGB during calibration and validation period was 7498 kg ha^{-1} and 3555 kg ha^{-1} and simulation was 5699 kg ha^{-1} and 3050 kg ha^{-1}, respectively.

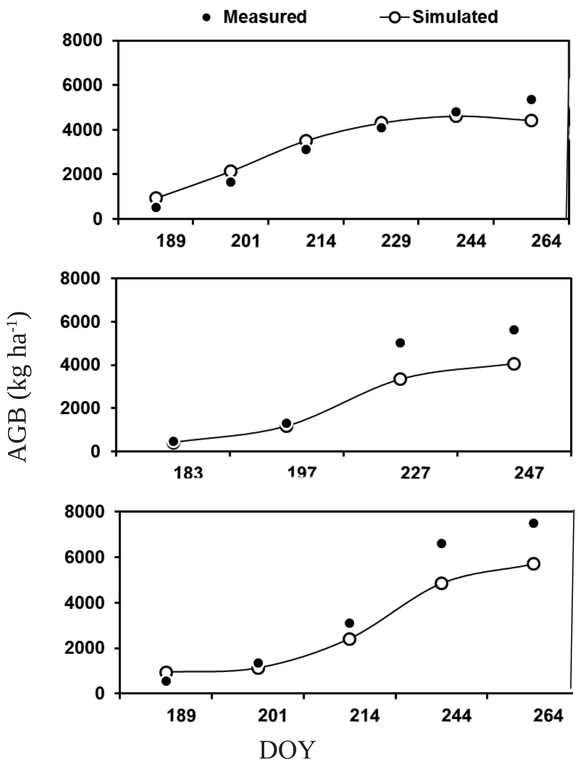


Figure 3. Comparison between measured and simulated above ground biomass (AGB) of cotton during different calibration years (a) 2000-NE, (b) 2001-NE, and (c) 2000-SE.

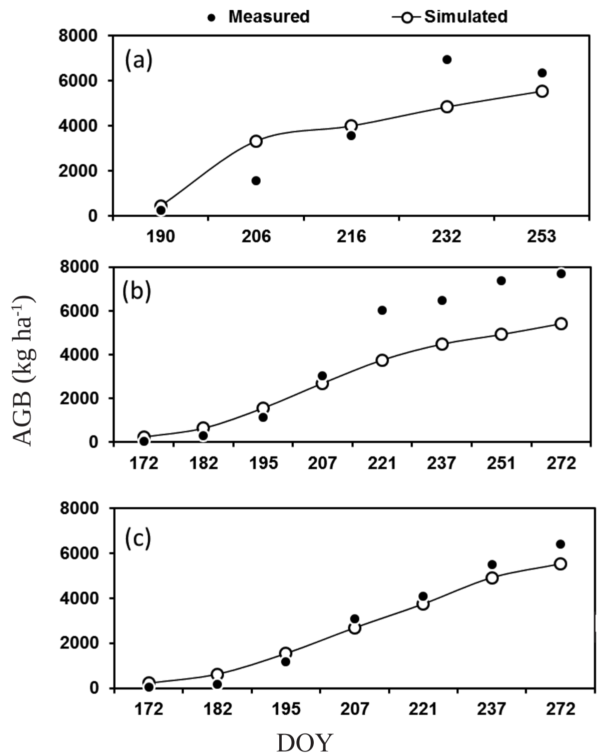


Figure 4. Comparison between measured and simulated above ground biomass (AGB) of cotton during different validation years (a) 2002-NE, (b) 2010-NE, and (c) 2010-SE.

Table 4. Comparison statistics between measured and simulated leaf area index (LAI), above ground biomass (AGB), evapotranspiration (ET), soil moisture at 0-20 cm depth, and lint yield during model calibration (2000-NE, 2000-SE, and 2001-NE) and validation (2002-NE, 2001-NE, and 2010-SE).

	r^2	*RMSE*	*d*	*PE (%)*
	Calibration			
LAI (m^2 m^{-2})	0.70	2.4	0.87	17.3
AGB (kg ha^{-1})	0.95	1.3	0.96	-7.36
ET (mm d^{-1})	0.94	0.7	0.98	3.2
Soil moisture (mm^3 mm^{-3})	0.77	2.80	0.75	7.47
Lint yield (kg ha^{-1})	0.93	1.66	0.97	1.45
	Validation			
LAI (m^2 m^{-2})	0.82	1.5	0.91	-0.85
AGB (kg ha^{-1})	0.89	1.6	0.93	-13.66
ET (mm d^{-1})	0.90	1.02	0.96	3.44
Soil moisture (mm^3 mm^{-3})	0.71	2.15	0.72	22.31
Lint yield (kg ha^{-1})	0.94	2.37	0.96	8.61

Where r^2 coefficient of determination, *RMSE* is Root Mean Square Error, *d* is index of agreement, and *PE* is Average Percent Error.

Evapotranspiration

Measured daily ET values from the lysimeter experiment were very close to the simulated seasonal ET values by the DSSAT-CROPGRO-Cotton model during both calibration and validation periods (Figs. 5 and 6). Similar to our results, Thorp et al. (2014) observed good agreement between measured and simulated ET in the FACE experiment conducted at Maricopa, Arizona, using the CROPGRO-Cotton model. The performance statistics for the comparison of measured and simulated ET during calibration and validation periods are presented in Table 4. During the 2000-NE calibration year the model underestimated the daily ET during emergence periods. Similarly, in the later stage of cotton growing seasons (218 to 240 DOY) the model over predicated ET, which was in accordance with LAI (Fig. 1a). Similar to 2000-NE calibration year, the model under simulated ET between 141 DOY and 150 DOY during 2001-NE, and between 137 DOY and ~150 DOY during 2000-SE, considered as the emergence of the cotton (Fig. 5b-c). During peak vegetative growth stage, the model underestimated ET during 2000-SE years (Fig. 5c) which was associated with the under prediction of LAI during that period. During validation years (Fig. 6a-c) the model underestimated ET during emergence, initial growth stage, and peak vegetative growth stage, and overestimated near maturity stage in all validation years. During 2002-NE validation year the model underestimated ET during 138 DOY to 152 DOY, 210 DOY to 240 DOY, and some other occasions. During 2010-NE and 2010-SE validation years the model underestimated ET from 138 DOY to 160 DOY, considered the early growth stage of cotton. The model also underestimated ET from 201 DOY to 256 DOY and during some occasions during the 2010-NE and 2010-SE validation years, which was associated with lower LAI (Fig. 2a-c). The overestimation of ET by the model when there was underestimated LAI and vice versa might be due to differences in the canopy temperature and air temperature. The CROPGRO-Cotton model assumes air temperature as the canopy temperature, which is the major limitation of

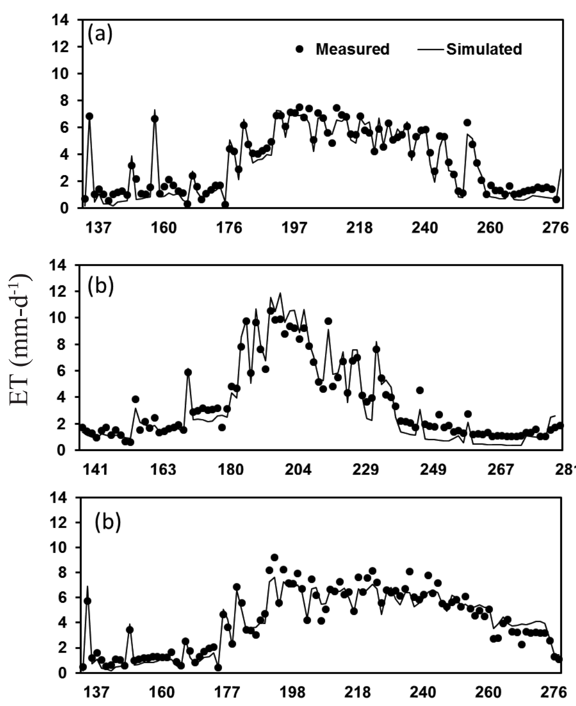


Figure 5. Comparison between measured and simulated daily cotton evapotranspiration (ET) during calibration years (a) 2000-NE, (b) 2001-NE, and (c) 2000-SE.

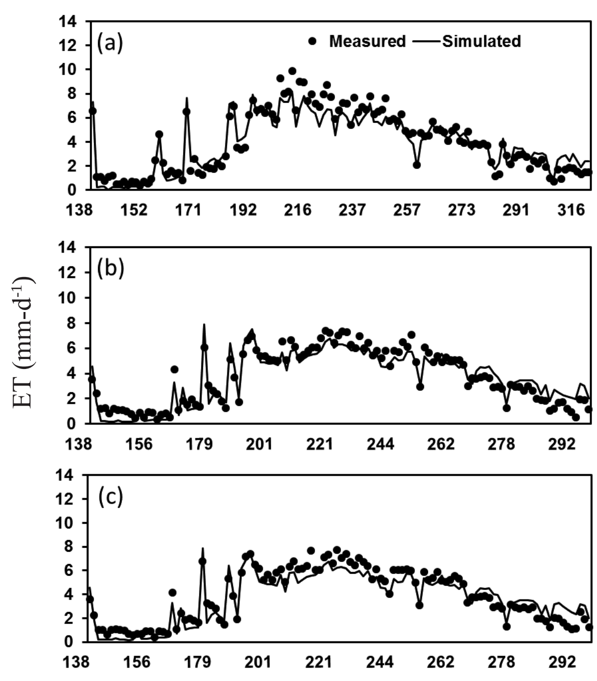


Figure 6. Comparison between measured and simulated daily cotton evapotranspiration (ET) during validation years (a) 2002-NE, (b) 2010-NE, and (c) 2010-SE.

this model. Usually canopy temperature is lower than the air temperature under well-watered conditions, due to evaporative cooling. Our study was conducted under irrigated conditions, and the difference in the canopy temperature and air temperature might have resulted in different simulated ET on those validation years. Average measured ET during calibration and validation were 3.76 and 3.86 mm d^{-1}, whereas simulated ET averages were 3.58 and 3.71 mm d^{-1}, respectively. Maximum measured (10.51 mm d^{-1}) and simulated (11.89 mm d^{-1}) ET were observed between 60-73 days after planting, during the peak vegetative growth stage.

Soil Moisture

Simulated and measured daily soil moisture including rainfall and irrigation amounts after cotton planting during calibration and validation years are presented in Figures 7 and 8. The CSM-CROPGRO-Cotton model predicted well the seasonal soil moisture content at 0-20 cm depth for both calibration (Fig. 7a-c) and validation (Fig. 8a-c) years. The model performance statistics such as r^2, d, and PE were 0.77, 0.75, and 7.47% during calibration and 0.71, 0.72, and 22.31% during validation, respectively. The corresponding values of RMSE were 2.81 mm^3 mm^{-3} and 2.15 mm^3 mm^{-3} during calibration and validation periods, respectively. The model responded very well with rainfall and precipitation events. For instance, the rainfall event of 35 mm occurred during 177 DOY of 2000 (Fig. 7a) and increased soil moisture from 0.19 mm^3 mm^{-3} to 0.35 mm^3 mm^{-3}. During calibration years (2000-NE, 2000-SE, and 2001-NE), average measured seasonal soil moisture at 0-20 cm depth ranged between 0.19 mm^3 mm^{-3} and 0.22 mm^3 mm^{-3}, whereas simulated average soil moisture at the same depth ranged between 0.17 mm^3 mm^{-3} and 0.20 mm^3 mm^{-3}. During validation years, (2002-NE, 2010-NE, and 2010-SE), average measured seasonal soil moisture ranged from 0.20 mm^3 mm^{-3} to 0.22 mm^3 mm^{-3} and simulated soil moisture ranged from 0.16 mm^3 mm^{-3} to 0.18 mm^3 mm^{-3} at 0-20 cm depth.

Lint Yield

The performance statistics between measured and simulated lint yield indicated by r^2, d, and PE were 0.93, 0.97, and 1.45% for calibration and 0.94, 0.96, and 8.61% for validation, respectively (Table 4). The CSM-CROPGRO-Cotton model predicted lint yield very well for both calibration and validation periods (Fig. 9a-b). The measured and simulated lint yields were higher during 2010-SE and 2010-NE than those observed during 2002-NE during validation, and might be due to the differences in planting date and seed rate (Table 1). Pettigrew et al. (2009) reported that early planting reduced cotton seed germination by 16% in the experiment conducted at Stoneville, MS. Similarly, another experiment conducted at a Mississippi cotton farm reported lint yield declines of 2.35 kg d^{-1} after the actual cotton harvesting day (Parvin et al. 2005). In the current experiment, cotton was planted on 21 May and harvested on 13 November during 2002, whereas during 2010 cotton was planted on 26 May and harvested on 28 October. In addition, the seed rate was higher during 2010 as compared to the 2002 cotton growing season (Table 1). Respectively, average measured and simulated lint yield was 960 kg ha^{-1} and 1006 kg ha^{-1} during calibration and 748 kg ha^{-1} and 803 kg ha^{-1} during the validation period.

Long Term Yield Simulation

The calibrated DSSAT-CROPGRO-Cotton model simulated lint yield for a period from 1924-2012 under irrigated conditions (Fig. 10). The calibrated model is able to demonstrate the effect of auto irrigation during dry, normal, and wet years for lint yield. Due to the implementation of auto-irrigation in the model, during the years of very low seasonal precipitation the model still simulated comparable lint yield with normal years. For instance, during years 2001, 2011, and 2012, the seasonal rainfall was well below 100 mm (dry years), yet the model still simulated a comparable amount of lint yield with the wet year.

Simulated averages with standard deviations of lint yield, ET, seasonal rainfall, and auto-irrigation during dry, normal, and wet years are presented in Table 5. Due to the implementation of auto-irrigation, no water stress was observed on lint yield even during the dry years; however, the amount of irrigation varied greatly. During the dry years, the amount of irrigation water ranged between 325 mm and 518 mm, during normal years

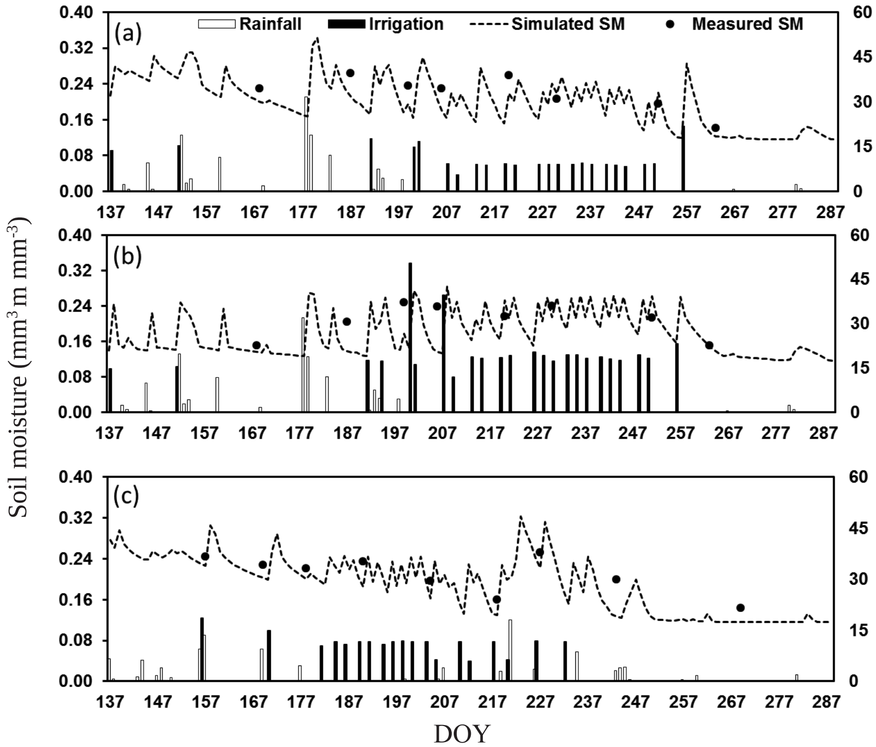


Figure 7. Comparison between measured and simulated daily soil moisture (SM) during calibration years (a) 2000-NE, (b) 2000-SE, and (c) 2001-NE at 0-20 cm depth.

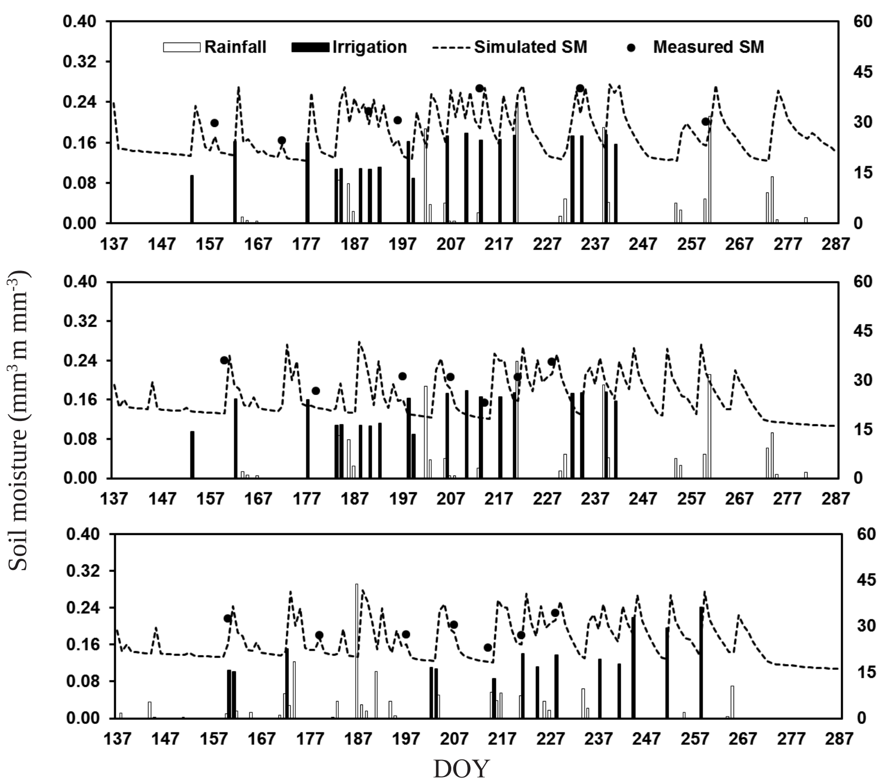
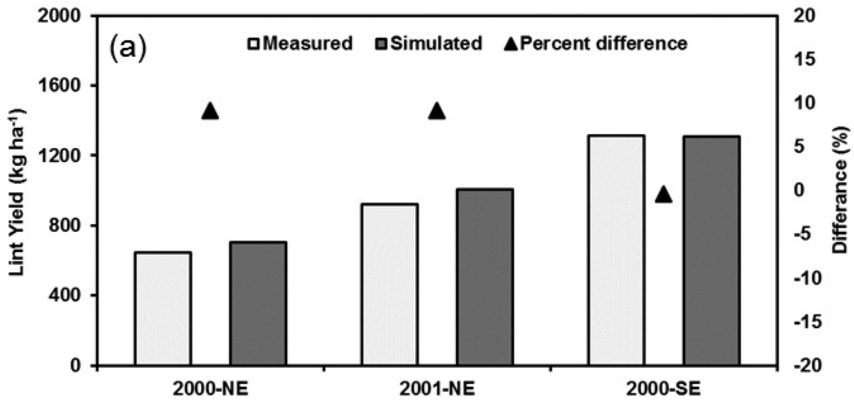


Figure 8. Comparison between measured and simulated daily soil moisture (SM) during validation years(a) 2002-NE, (b) 2010-NE, and (c) 2010-SE at 0-20 cm depth.



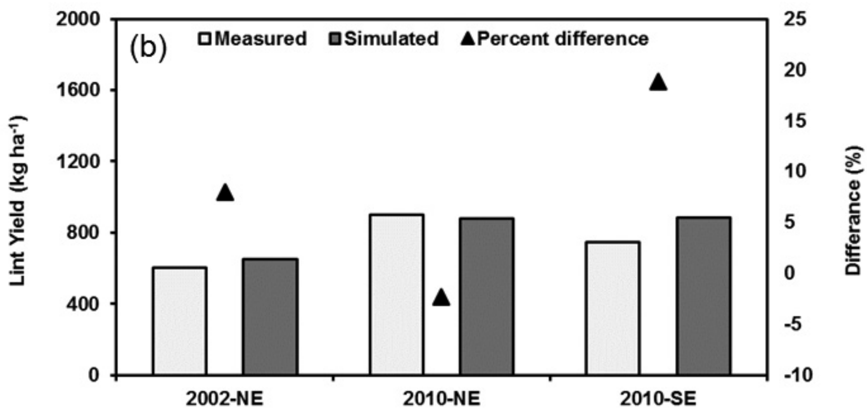


Figure 9. Comparison and percent difference between measured and simulated lint yield in the different cotton growing seasons during (a) calibration and (b) validation.

Table 5. DSSAT-CSM simulated historic (1924-2012) average with standard deviation of lint yield, evapotranspiration, seasonal rainfall, and auto-irrigation during dry, normal, and wet years at Bushland, TX.

	-------------- Irrigated --------------			
Years	**Average lint yield ($kg\ ha^{-1}$)**	**ET ($mm\ d^{-1}$)**	**Average seasonal rainfall (mm)**	**Auto-irrigation (mm)**
Dry years	615±88	567±28	132±50	419±57
Normal years	557±28	557±29	286±58	306±46
Wet years	629±169	570±29	493±84	208±35

between 218 mm and 403 mm, and during wet years between 118 mm and 348 mm. The results indicate that during dry years, an average of 37% more irrigating water was required when compared to normal years, and 99% more water was required compared to wet years. Simulated ET, lint yield, and auto irrigation under dry, normal, and wet years were least variable (CV<0.15). Rainfall and auto irrigation were moderately variable, with coefficients of variation (CV) ranging between 0.20 and 0.29, according to Wilding (1985) criteria (CV<0.15 as the least, 0-15<CV<0.35 as moderate, and CV>0.35 as the most variable).

Conclusions

A well-calibrated DSSAT-CROPGRO-Cotton model was established for the Bushland, TX study site, using field measured lysimeter data under irrigated conditions. The calibrated model is able to simulate crop phonological stages including LAI, AGB, ET, soil moisture, and lint yield. The simulated phonological stages such as emergence, anthesis, and physiological maturity date were within the range of the measured range for the THP regions. Twelve cultivar and five ecotype parameters were adjusted during the model calibration process. Good agreement was observed between measured and simulated LAI, AGB, seasonal ET, seasonal soil moisture, and lint yield during calibration and validation processes, as indicated by the performance statistics. The performance statistics for LAI during calibration were $r^2 = 0.82$, $d = 0.96$, and $PE = 0.19$ and were $r^2 = 0.93$, $d = 0.93$, and $PE = -3.74$ during validation. The calibrated model was able to simulate historic (1924-2012) lint yield during dry, normal, and wet years. During the dry years, THP cotton required an average of 37% and 99% more irrigation water when compared to normal and wet years, respectively. The results imply that there is a need for ET based irrigation management strategies in the THP, especially during the dry years, for which the current calibrated DSSAT-CROPGRO-Cotton model could be used.

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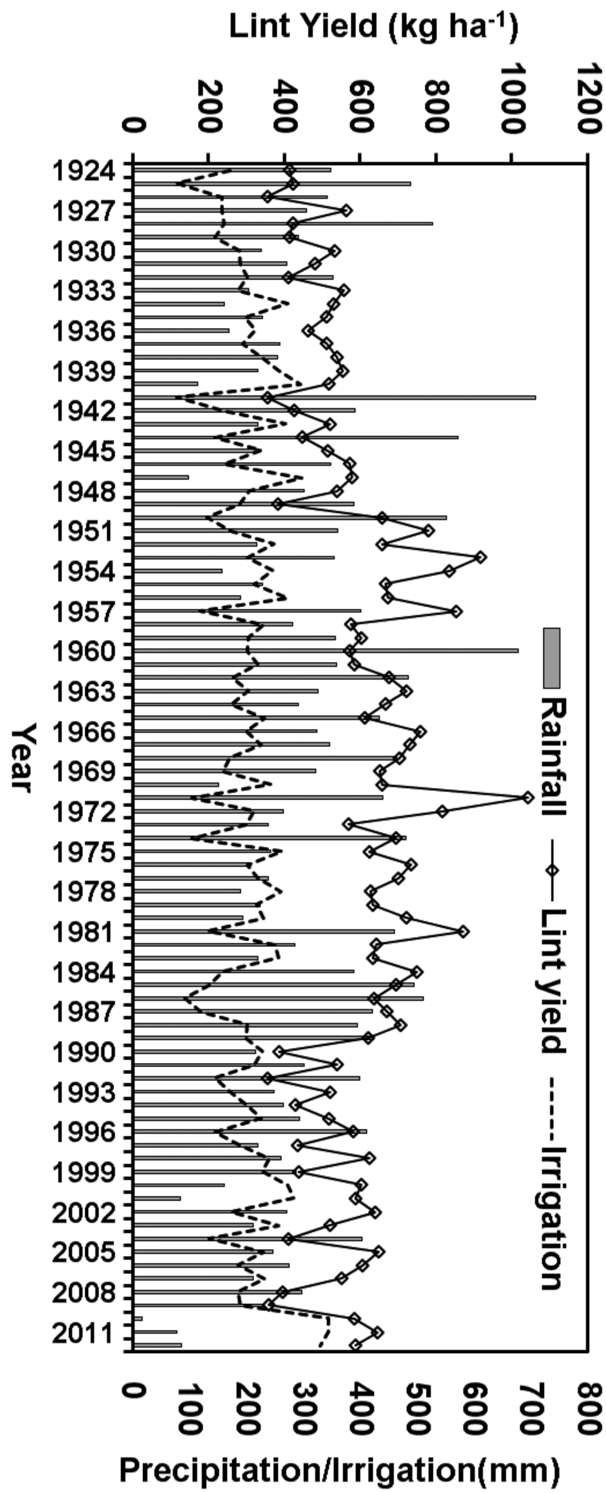

Figure 10. Simulated long term (1924-2012) lint yield (red line), auto irrigation (black line), and measured rainfall at Bushland, TX.

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Understanding Climate-Hydrologic-Human Interactions to Guide Groundwater Model Development for Southern High Plains

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Abstract: The Ogallala Aquifer is the only reliable source of freshwater in the Southern High Plains (SHP) and is used extensively to build a strong agricultural economy with a significant impact on global food security. Groundwater models capable of simulating human-hydrologic-climate interactions are crucial to guide future water management and policy planning endeavors in this water stressed region. A well-defined conceptual model is a necessary first-step in that direction. Conceptual modeling should not be limited to compiling necessary datasets but must also focus on generating critical insights pertaining to human-climate-aquifer interactions especially when the emphasis is on guiding future policy. Model integration and the feasibility of coupling available tools and techniques must be explored to fill-in critical data gaps and capture interactions with a high degree of fidelity. A conceptual modeling framework built on this premise was applied to guide an on-going regional-scale groundwater modeling study in the SHP. The paucity of groundwater production data was identified as a major limiting factor. A linked Decision Support System for Agro-Technology Transfer (DSSAT) model with MODFLOW is expected to be useful in obtaining groundwater production estimates through detailed crop modeling. The time to recharge is long (decades to centuries) over most of the SHP. As such, the coupling of watershed and groundwater models is perhaps not warranted. Baseflow separation indicated that surface water-groundwater interactions have diminished over the last six decades due to declining water tables. While groundwater withdrawals generally increased during droughts, the aquifer also buffered climatic influences at some locations.

Keywords: *Ogallala Aquifer, model calibration, conceptual model, climate change*

With erratic and unreliable rainfall, groundwater is often the only reliable source of water in arid and semi-arid regions and continues to be over-exploited in many parts of the world. As irrigated agriculture is a major user of groundwater, dwindling aquifer resources negatively impact rural economies and threaten global food security (Hanjra and Qureshi 2010; Wang et al. 2017). In addition to the economic benefits of groundwater resources, groundwater discharge through springs and stream baseflow sustains certain groundwater-dependent ecosystems (Griebler and Avramov 2014). Therefore, groundwater is valuable for both economic and ecological considerations.

Groundwater is often considered a private property and has not been subject to extensive regulation in many parts of the world (Uddameri 2005). However, there is a growing recognition that aquifers should be proactively managed if groundwater resources are to be available to future generations. Management of groundwater resources often requires a careful balancing of the needs of the current generation (intra-generational equity) against those of the future (inter-generational equity). As groundwater is an exhaustible resource, the question of how much groundwater should be currently used (or how much should be left as a resource stock for the future?) is fundamental to (ground)water resources planning endeavors.

Groundwater planning requires projections of climate and associated human adaptations well into the future. Current limited understanding of the likely future climate trajectories introduces a significant amount of uncertainty during groundwater planning endeavors. Climate projections over much of the arid and semi-arid portions of the United States indicate that even while the total annual precipitation may not likely change significantly, there will be marked shifts in winter and summer precipitation patterns and a greater propensity for droughts during the growing season (Swain and Hayhoe 2015). Groundwater is considered a buffer resource and it is increasingly relied upon during periods of droughts (Tsur 1990), often exacerbating the already existing scarcity (Shahid and Hazarika 2010) and causing negative impacts on groundwater dependent ecosystems. While groundwater responses to droughts are not fully understood, a recent study indicates that groundwater production in the High Plains exhibits a strong correlation to climate states, and the stresses on the aquifer increase substantially during dry periods (Whittemore et al. 2016).

Groundwater models form the backbone of water resources planning and management endeavors in many regions of the world such as Bosnia and Herzegovina (Ireson et al. 2006), Greece (Pisinaras et al. 2007), and Denmark (Refsgaard et al. 2010). Regional-scale groundwater flow models are needed to quantify the current and future states of the aquifer. Groundwater states can be defined based on hydraulic heads (or the more intuitive saturated thickness, in case of unconfined aquifers) as well as fluxes to other hydrologic, human, and atmospheric sub-systems with which the aquifer interacts (Uddameri et al. 2014). Groundwater models are often coupled with economic and optimization routines to identify how much water can be optimally extracted at a given location and over a planning horizon (MacEwan et al. 2017). Groundwater production can be limited in space and time due to physical and policy constraints that are imposed within these hydro-economic models (Uddameri and Kuchanur 2007). Clearly, the validity of any groundwater policies or best management practices arising from the use of hydro-economic models hinges to a large degree on the performance of the underlying groundwater flow model and its ability to simulate pertinent hydrogeologic processes.

Existing groundwater flow simulators such as MODFLOW (McDonald and Harbaugh 1988; Harbaugh 2005) are routinely being employed to develop regional groundwater flow models that guide groundwater policy and management studies (Hernandez et al. 2013). MODFLOW not only describes the regional hydrogeology but also captures the interactions of aquifers with human, atmospheric, and surface water systems via boundary conditions. These boundary conditions are implemented as specialized packages (e.g., well package for anthropogenic withdrawal; recharge package for groundwater-atmospheric interactions; and river package for surface water-groundwater interactions) and called during the simulation, as necessary. The parameterization of these boundary conditions is, however, parsimonious and as such, MODFLOW may not capture the human, hydrologic, and climate interactions with a high degree of fidelity. The coupling of MODFLOW with detailed simulators of other hydrologic, human, and climate systems (Kim et al. 2008; Reeves and Zellner 2010; Dawes et al. 2012; Bailey et al. 2017) has been employed to explicitly model changes in climate, land use, and other anthropogenic alterations with a greater degree of sophistication.

The integration of groundwater models with other simulators is certainly pragmatic and provides a comprehensive framework to consider climate and anthropogenic stresses in a rigorous manner and must be looked into critically. The coupling of climate, watershed, and vadose zone models with groundwater simulators, undoubtedly opens exciting opportunities to specify groundwater boundary conditions in a realistic manner and helps minimize the arbitrariness associated with the propagation of climate and anthropogenic stresses through groundwater systems. Many hydro-climatic variables exhibit considerable persistence and even with the availability of relatively long datasets, the information content is only sufficient to support hydrologic models of limited complexity (Jakeman and Hornberger 1993). In addition, such a coupling increases the data requirements, poses additional computational burden, and adds complexity to the calibration process, as there will be more parameters to calibrate. Therefore, the nature and extent of model integration must be carefully considered during the model development stage.

The required inputs needed to run a groundwater model are seldom available in regional-scale studies. As such, inverse modeling or calibration must be used. Calibration entails adjusting unknown model inputs until the observed state variables (i.e., hydraulic heads and fluxes) reasonably match observed field data. The inverse modeling of groundwater systems is mathematically ill-posed (Yeh 1986). The non-uniqueness of model calibration implies several plausible unknown input ensembles (i.e., model inputs with values within acceptable ranges for a given aquifer system) can yield statistically similar fits to observed data. The problems of non-uniqueness and ill-posedness are not exclusive to groundwater models and hold true for other social and earth systems models as well (Oreskes et al. 1994). Therefore, these problems are likely to get amplified when calibrating integrated models. The situation clearly worsens when the available observational data are limited.

Research Questions

The study is based on the premise that conceptual modeling of the groundwater system must not just focus on identifying proper inputs required by the groundwater flow simulator, but must also take a holistic overview and identify important interactions at the groundwater boundaries and find efficient ways to incorporate them into groundwater models. Proper parameterization of climate-hydrologic-human interactions with aquifer systems is critical if groundwater models are to be used in future policy planning and management endeavors, in light of climate and land-use changes. Therefore, the study seeks to evaluate: 1) The importance of surface water-groundwater interactions within the chosen model domain; 2) If explicit coupling of watershed models with groundwater models is warranted to capture atmosphere-land-aquifer interactions; and 3) Limitations in simulating human-aquifer interactions and finding alternative approaches to fill this critical data gap. The study demonstrates the utility of several simple "first-cut" analysis techniques to evaluate groundwater interactions with other interconnected systems. These tools and techniques are illustrated by applying them in a groundwater model development study focused on the southern regions of the Ogallala Aquifer.

Study Area and Modeling Context

The primary focus of the study is the Ogallala Aquifer, which underlies a tristate area encompassing Texas, New Mexico, and Oklahoma, also referred to as the Southern High Plains (SHP) for brevity. However, the groundwater model domain extends into regions of Kansas and Colorado to minimize boundary effects on the study area of interest. Therefore, the active model domain in Kansas and Colorado is depicted as hatched areas on maps presented in this paper. The SHP produces over 20% of the cotton grown in the U.S. and is also a major producer of corn, sorghum, peanuts, and winter wheat (USDA-NASS 2017). The SHP is also a top beef producing region in the U.S. (Allen et al. 2012). Groundwater from the Ogallala Aquifer has been extensively relied on, as surface water sources are extremely limited in this semi-arid region (see Figure 1). Groundwater production in the region is very high; over 90% of the crops grown rely on irrigation (Colaizzi et al. 2009). Groundwater over-exploitation has caused severe water level declines in the SHP region. The saturated thickness of the aquifer has dropped 30.5 m (100 ft) – 45.7 m (150 ft) since groundwater production began in earnest in the 1950s (McGuire 2012). The available saturated thickness is close to the practical depletion limit of 9 m (30 ft), often considered the lower threshold to sustain irrigated agriculture in the region (Buddemeier et al. 2003; Ng et al. 2010).

The current modeling effort is part of a larger study that seeks to develop a groundwater modeling framework to support future hydro-economic modeling efforts in the region, explicitly considering climate variability and change (Tewari et al. 2015). The hydro-economic models

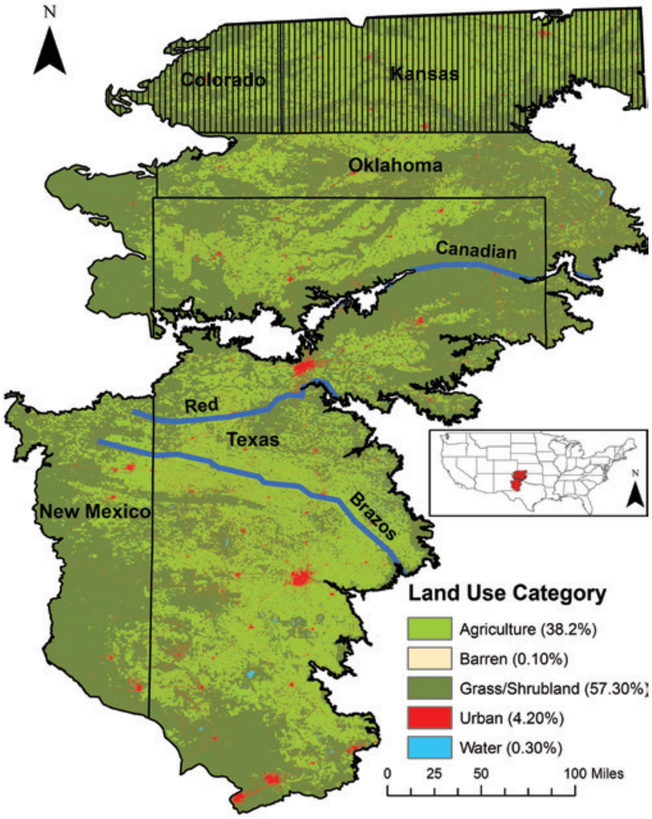

Figure 1. Land use land cover characteristics in the Southern High Plains (Hatched area represents regions of Kansas and Colorado that are included in the groundwater model domain to minimize boundary effects but are not of interest here.) (Data from: USDA – Cropscape data for 2016 - Bouryan et al. 2011). View color map at: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.

generally seek to identify optimal groundwater development strategies that maximize net revenue. The existing groundwater management doctrines and groundwater management approaches provide the underlying basis for hydro-economic model development efforts and as such, must be understood as they provide the context for the present groundwater modeling efforts. Groundwater resources are managed differently in the three states (Texas, Oklahoma, and New Mexico) of interest here. However, stakeholder driven regional-scale planning has been adopted by all states.

Figure 2 shows the regional water planning groups and other water management institutions within the three-state region of interest. In Oklahoma, groundwater is considered a private property right and belongs to the overlying surface owner, but is subjected to reasonable regulation by the Oklahoma Water Resources Board (OWRB). Reasonable regulation is defined based on maximum annual yield which allows for a basin to have at least 20 years life of the aquifer. The maximum annual yield is used as a basis for permitting groundwater. A permit application is approved as long as the ownership over which the groundwater production takes place is established and the produced water is not wasted and is put to beneficial use. Well spacing guidelines are also used as part of the permitting process (OWRB 2016).

Texas has adopted a multi-tier water planning and management process. The state is divided into 16 regional water planning groups (RWPG) that consider both surface and groundwater resources within their region but are set largely along river basins. Groundwater is considered a private property but can be managed locally by political subdivisions called Groundwater Conservation Districts (GCDs) which sometimes coincide with county boundaries. Neighboring GCDs are also grouped into Groundwater Management Areas (GMAs) which engage in regional-scale groundwater planning. In New Mexico, groundwater law is based on the doctrine of prior appropriation. The State Engineer has jurisdiction over all declared groundwater basins in the state. There are 108 separate groundwater basins or extensions of groundwater basins in the state. Currently, every parcel of land in the state is covered under a groundwater basin and as such, the Office of the State Engineer has control over all the groundwater in the State. Groundwater development rights or permits to produce groundwater are obtained from the State Engineer, with senior rights holders getting precedence over junior rights holders (Brockmann 2009). While the underlying doctrines of groundwater management vary across the model domain, there is consensus that groundwater resources are extremely important for economic vitality of the SHP region. In addition, the ecological and environmental significance of groundwater are also well recognized (PLJV 2017a).

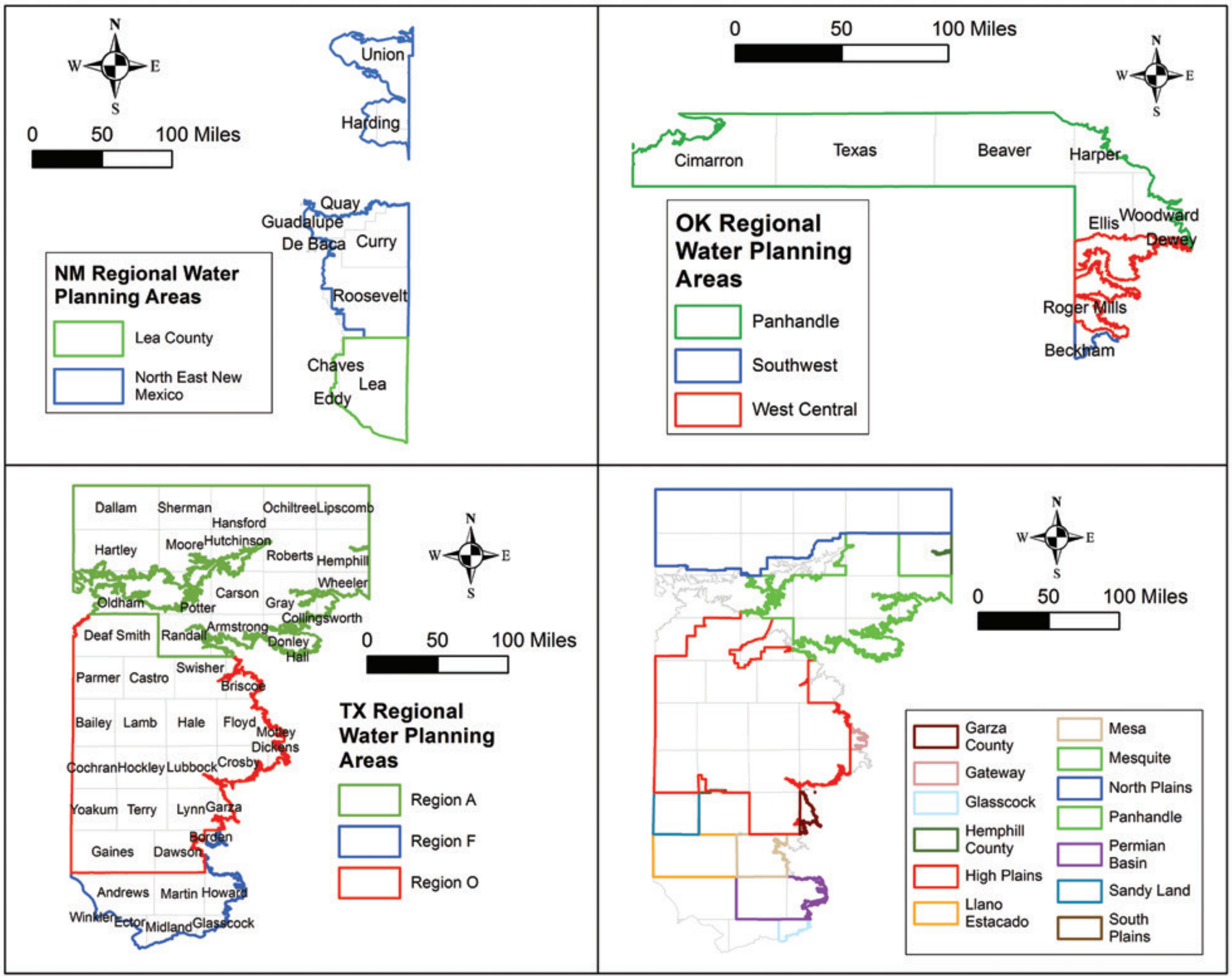

Figure 2. Water management institutions and their jurisdictions in Texas, New Mexico, and Oklahoma.

Surface Water - Groundwater Interactions

Figure 3 depicts the major surface water bodies in the region. The major rivers within the study domain include the Brazos River and its tributaries, the Red River, and the Canadian River. Several ephemeral streams that channel runoff associated with large rainfall events can also be seen in Figure 3. Other surface water bodies include several small sized reservoirs and intermittent ponds. The study area also has a large number of 'playas' or shallow wetland systems that are ephemerally filled by rainfall events.

Baseflow represents the subsurface (groundwater) discharges into surface water bodies and are the only source of surface water flows during periods without significant rainfall. Baseflow assessments are critical in the evaluation of low flow characteristics of the streams, and are used in water supply, water and ecological management, and even pollution assessment studies (Arnold et al. 1995). Baseflows are an important component of the hydrologic budgets that are often used to estimate recharge to groundwater (Arnold and Allen 1999). Baseflow separation was carried out using the recursive filter approach of Nathan and McMahon (1990). In this approach, the streamflow record is separated into high frequency (overland flow) and low frequency (baseflow) components. Digital filters remove the subjectivity and arbitrariness associated with graphical baseflow separation techniques, and are noted to perform well against other manual and graphical methods when compared against field datasets (Arnold et al. 1995).

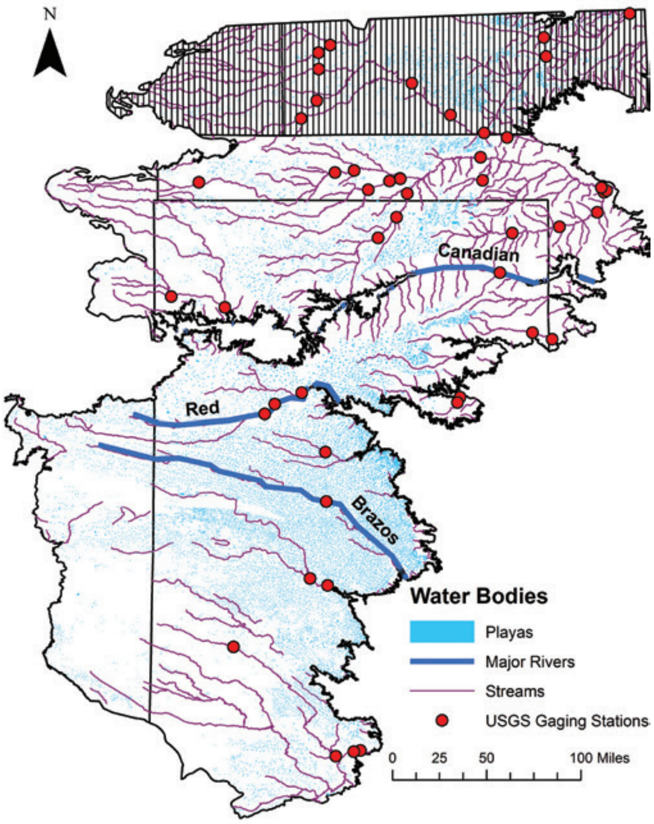

Figure 3. Surface water bodies in the Southern High Plains regions.

The separated baseflow estimates at four different USGS gaging stations on the major rivers (Figure 1) are depicted in Figure 4. Except for the Canadian River, the baseflows are generally low, typically in the order of 0.028 – 0.28 m^3/s (1 – 10 cubic feet per second (cfs)). The magnitude of baseflows has diminished considerably after 1960, particularly in the Canadian River. This decline coincides with the increased groundwater withdrawals that started around 1950 due to rural electrification and intensification of irrigated agriculture in the region (USGS 1960; Deeds et al. 2015). The hydraulic head from groundwater data collected by the Texas Water Development Board (TWDB) and stream stage values measured by USGS were interpolated to estimate the hydraulic driving force between the stream and the aquifer during pre-development (pre-1950) and current (year 2013) conditions, shown in Figure 5. The pre-development river stage was interpolated based on the stage-discharge curve constructed at USGS gaging station 07228000, which was assumed to hold true over the length of the river segment. The stream stage was then converted to hydraulic head (above MSL using a 10 m Digital Elevation Model). This head was compared against interpolated hydraulic head surface developed using groundwater data from the TWDB, in conjunction with inverse distance weighting (IDW) scheme. The driving force for groundwater discharges (baseflows) has considerably diminished, due to water level declines over time, and corroborate the results obtained from baseflow separation techniques.

The baseflow analysis indicates that surface water-groundwater interactions are not of significance (as of 2013) within the study area and are mostly localized to riparian discharge areas. Given the limited connectivity between the surface water bodies and the underlying aquifer, detailed modeling of surface water-groundwater interactions is perhaps not warranted for simulations of agricultural (or general human consumption) water use. Therefore, the major rivers within the model domain could be simulated using the MODFLOW RIVER package. The RIVER package uses the concept of conductance (a measure of river-aquifer connectivity) and the relative head difference (hydraulic driving force) between the stream-stage and the aquifer hydraulic head underlying the river bed to calculate fluxes in and out of the aquifer (Harbaugh 2005). However, the RIVER package could potentially act as an infinite source of water to the aquifer and as such, caution must be exercised when placing wells close to river boundaries. While the RIVER package has traditionally been used in previous modeling studies (Deeds et al. 2015), the streamflow routing (SFR) package is also another option and perhaps provides a more realistic representation of the stream-aquifer dynamics in the region albeit with higher data requirements.

Atmosphere - Land - Soil - Aquifer Interactions

Groundwater Evapotranspiration

Evapotranspiration (ET) is another important atmosphere-land-soil-aquifer interaction. In the context of groundwater modeling, ET refers to the uptake of groundwater by plants. Phreatophytic

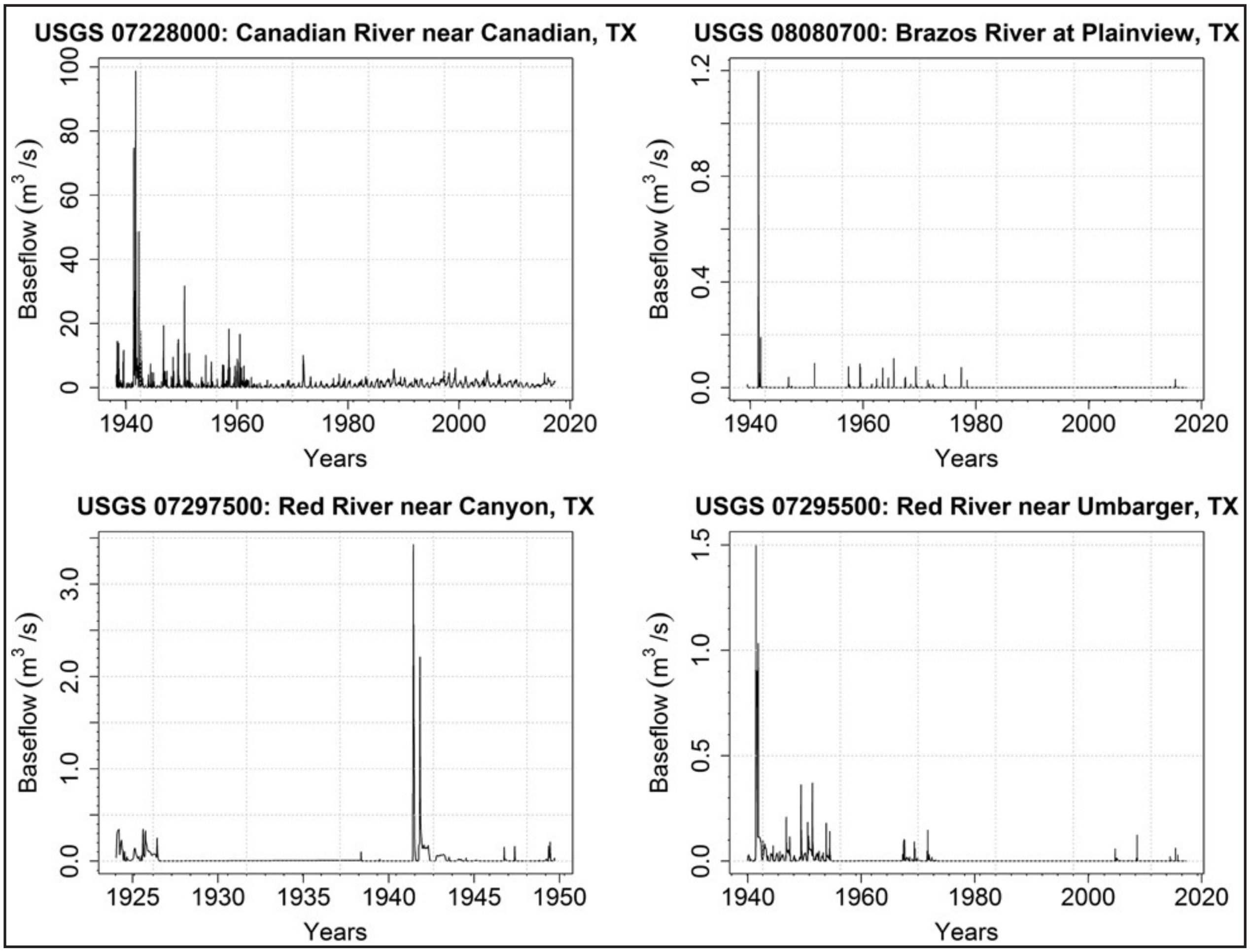

Figure 4. Estimated baseflows in major rivers within the study area.

uptake of water is considered an important mechanism in riparian areas. Several important phreatophytes, including hackberry (Celtis laevigata), honey mesquite (Prosopis glandulosa), cedar elm (Ulmus crassifolia), Ashe juniper (Juniperus ashei), Shin oak (Quercus sinuate), and American elm (Ulmus americana), have been found to have rooting depths ranging from 7 m (23.0 ft) to 22 m (72.2 ft) (Jackson et al. 1999; Scanlon et al. 2005). Mapping of phreatophytes and monitoring their groundwater uptake has not been undertaken in Texas or Oklahoma (Scanlon et al. 2005). However, the national wetlands database can be used to map riparian areas (FWS 2017). While phreatophyte uptake of water has been monitored to some degree in New Mexico (Tamarisk Coalition 2005), no documented studies were found within the portions of New Mexico underlain by the Ogallala Aquifer. Phreatophytes can be found scattered on rangelands where plants tap into any locally perched alluvium deposits or other shallow subsurface water sources (e.g., infiltration from playas). Based on the estimates provided in Scanlon et al. (2005), the uptake of water from phreatophytes generally is smaller than water produced for irrigation and livestock uses. Ahring and Steward (2012) indicate that phreatophyte tree populations decrease considerably when the depth to water table becomes larger than three meters (10 ft). Groundwater ET is unlikely to be an important process on a larger regional-scale in the SHP as the depth to water table is typically greater than 30 m (100 ft) (Gautentag et al. 1984).

Groundwater Recharge

Groundwater recharge occurs when rainfall (atmospheric water) percolates through the vadose zone to the water table. Recharge is the primary

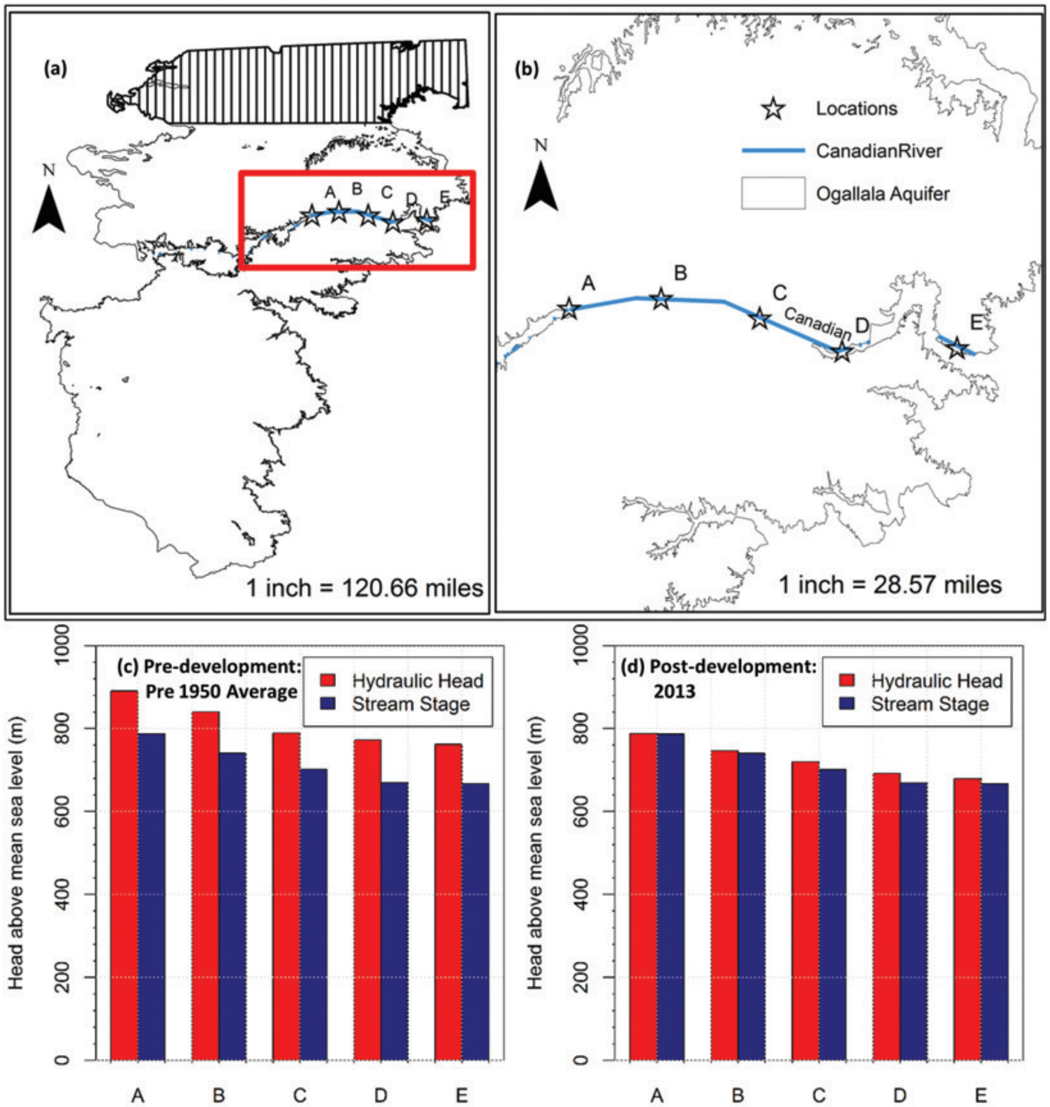

Figure 5. Hydraulic driving force (groundwater level – stream stage) along the Canadian River in the study area: a) Map of the Canadian River; b) Locations on the river where the driving force has been estimated; c) Pre-development conditions; and d) Current conditions.

source of water to the Ogallala Aquifer and represents a major atmospheric-land-soil-aquifer interaction. While recharge represents atmospheric water, the vadose zone plays an important role in transmitting the water to the aquifer. Recharge within the study area can be categorized into three components: 1) Recharge in upland areas; 2) Recharge from playas; and 3) Recharge from ephemeral streambeds in the region.

Infiltration of rainfall into the subsurface is the first step of the recharge process. However, a significant portion of the infiltrated water will likely be taken up by roots and lost via evaporation within the root zone (typically 1 – 1.5 m bgs). Upward moisture fluxes can also occur past the root zone, especially under native grassland conditions (Scanlon et al. 2003), but are generally noted to be downward under both rain-fed and irrigated agricultural lands within the study area (Ng et al. 2009). Percolation (and subsequent recharge) rates can vary considerably and are known to exhibit episodic behavior (Ng et al. 2010). Recharge depicts a strong dependence not only on the amount of rainfall but also on the timing of the rainfall events, especially in relation to crop emergence (Ng et al. 2010). Rainfall that occurs in winter, when there is low ET uptake by plants and greater soil moisture availability, is more likely to recharge the aquifer than precipitation during growing seasons. There is considerable variability associated with projections of recharge under future climate states. However, modeling studies indicate that small changes in precipitation cause large alterations in recharge (Crosbie et al. 2013). Land use alterations and changes in vegetation cover are also known to play an important role in controlling diffuse recharge rates. The replacement of deep-rooted vegetation with shallow-rooted crops is noted to increase diffuse recharge rates (Cook et al. 1989). Recharge from upland areas is generally considered to be low within the study area (Taghvaeian et al. 2017). Keese et al. (2005) used modeling to estimate annual diffuse recharge to be in the range 0.4 mm/yr (0.02 in/yr) – 0.8 mm/yr (0.03 in/ yr), which is about 0.1% of the annual average rainfall.

Playas (ephemeral, closed-basin wetlands) are considered to be important recharge zones within the southern portions of the Ogallala Aquifer. Runoff water collects into playas, allowing for the water to percolate into the soil even after the cessation of rainfall. However, settling of sediments and deposition of fine particulates at the bottom reduce the infiltration capabilities of many playas over time. The saturated hydraulic conductivity of these bottom clay deposits can be low, in the order of 10^{-7} – 10^{-6} cm/s (3.28 x 10^{-9} – 3.28 x 10^{-8} ft/s) (Zartman et al. 1994). Focused playa infiltration and recharge is hypothesized to occur from the outer basin and annulus (Zartman et al. 1996), and therefore varies with rainfall depths. Macropore distributions in the playas also play a major role in controlling downward water fluxes (Wood et al. 1997). Recharge rates in playas are generally 1 to 2 orders magnitude higher than interplaya settings (Gurdak and Roe 2010). However, downward fluxes from playas can be highly variable, and range from zero to about 254 mm/yr (10 in/yr) (PLJV 2017b). Based on chloride mass balance studies, Wood and Sandford (1995) conclude that the annual recharge in the region is 11 ± 2 mm/yr (0.43 ± 0.08 in/yr), and nearly 60% - 80% of this comes from macropore recharge in the playas. Playas come in a variety of sizes, but the median playa area is less than 0.024 km^2 (6 acres). While playas occupy less than 2% of the study area, they play an unusually important role in controlling local recharge. However, the scale of the playas relative to the model discretization (1 sq. km ~ 250 acres) makes it rather difficult to capture playa recharge in an explicit manner. The playa density within the model grids can however be used as a factor to guide the calibration of recharge.

Infiltration and subsequent recharge of rainfall through ephemeral and intermittent streambeds is a potential local pathway for recharge (Shanafield and Cook 2014). Modeling studies conducted in other arid and semi-arid regions of the world indicate that recharge from transmission losses in intermittent and ephemeral streams can be high (in the order of 1 m/yr (3.28 ft/yr)), but exhibit considerable variability (Shanafield and Cook 2014). In addition, recharge from streams tends to be localized and results in mounding below the streambed. The silt and fines deposited by the floodwaters in the downstream regions have been noted to effectively seal the channel bottom and cut-off any infiltration even under high flowrates (Missimer et al. 2012). Therefore, contributions of streambed recharge tend to diminish over time (Kustu et al. 2010; Korus et al. 2017). A review of literature indicated that streambed recharge has not been extensively studied within the study area, but is not likely a dominant mechanism due to deep water tables, and also because runoff likely is concentrated in playas (local topographic lows) and/or is lost due to high evaporative rates.

There are essentially four basic strategies for including recharge in groundwater models. These strategies with increasing degree of complexity are: 1) Calibrate recharge fluxes directly; 2) Use semi-empirical equations that correlate recharge with precipitation and/or soil properties to guide calibration; 3) Use a watershed model such as the soil water assessment tool (SWAT) (Srinivasan et al. 1995) or the soil water balance (SWB) model (Westenbroek et al. 2010) to compute deep percolation, and use that estimate as an input to the groundwater flow model; and 4) Integrate a watershed model with an unsaturated zone model to quantify and properly route the water leaving the root zone through the vadose zone, and use the computed recharge as a direct input to the groundwater flow model. The first approach, while simplistic, might lead to a highly over-determined system if recharge were individually assigned for each active model cell. The second strategy represents an improvement, but its accuracy depends upon how well the semi-empirical equation models the recharge. The third approach where a watershed model is used to estimate aquifer recharge seems certainly pragmatic and presents a good way to incorporate climate-land-soil-aquifer interaction, especially when the water table is shallow (so the travel time in the vadose zone can be neglected), or when the dominant component of recharge is occurring through fast paths rather than slow matrix diffusion. Finally, the fourth approach, while most rigorous of all, greatly adds complexity to the modeling process.

The time taken for a wetting front leaving the root zone to make it to the water table is a key factor in assessing which strategy to adopt. When travel times are long, direct coupling of SWAT and MODFLOW simulators will overestimate recharge during early times of the simulation, as the time for water to percolate through the deep vadose zone is not explicitly considered. Calibration and running of integrated watershed-vadose zone-groundwater models will require considerable amounts of data and add computational burden. As the number of unknown model inputs increase, the parametric uncertainties in the model estimated outputs increase. These modeling limitations can outweigh the benefits of integration, especially when the recharge fluxes are small. In the present study, semi-empirical equations based on output from a vadose zone model are used to obtain initial estimates for aquifer recharge.

Water Transit Times through the Vadose Zone

While infiltration at the land surface tends to be episodic, wetting fronts continue to move downward and cause redistribution of moisture long after the cessation of rainfall (Stephens 1995). A preliminary estimate of the time required for a parcel of water to move from the bottom of the root zone (~ 1 m (3.28 ft) below ground surface) to the water table can be computed using Equation 1.

$$t_w = \frac{L}{K(\bar{\theta})} \tag{1}$$

Where t_w is the travel time for a parcel of water to percolate from the root zone to the water table; L is the distance between the water table and the bottom of the root zone; and K is the effective unsaturated hydraulic conductivity, which is a function of the moisture content (θ). Equation 1 is dimensionally consistent and works with any consistent set of units. The average moisture content in the vadose zone was computed in this study following the approach suggested by Sousa et al. (2013), wherein the capillary (suction) head is assumed to be equal to the potential (gravitational) head at any point in the vadose zone. Using the van Genuchten-Maulem capillary pressure-saturation-hydraulic conductivity relationship (van Genuchten 1980), the effective hydraulic conductivity employing the Sousa et al. (2013) approach can be estimated as:

$$K(\bar{\theta}) = \int_0^L \frac{\{1 - (\alpha z)^{n-2}\{1 + (\alpha z)^n\}^{-m}\}^2}{(1 + (\alpha z)^n)^{m/2}} K_s dz$$
$$\text{where } m = 1 - \frac{1}{n} \text{ and } 0 < m < 1 \tag{2}$$

Where α, n, and m are van Genuchten model parameters and z is the pressure head, a function of soil-water content. This approach is known to over-predict hydraulic conductivity and therefore underestimate the travel time in the vadose zone (Sousa et al. 2013). Also, as ET is not considered and a unit hydraulic gradient is assumed, the estimate provided by Equation 1 in conjunction with Equation 2 can be considered as an "optimistic" or shortest travel time estimate. The van Genuchten model parameters, α and n, were estimated using pedo-transfer functions developed by Vereecken (1989), as reported by Loosvelt et al. (2011). The saturated hydraulic conductivity, K_s, was estimated using the relationship provided in Saxton and Rawls (2006). The STATSGO database was used to obtain spatially variable sand, clay, organic matter, and bulk density values needed by the pedo-transfer functions.

The time for a parcel of water to travel from the bottom of the root zone to the water table was calculated over the model domain and is depicted in Figure 6. As can be seen, the estimated time is on the order of several decades to centuries, except near the aquifer boundaries where the aquifer is relatively thin. These estimates are consistent with transit times presented in the literature in the high plains aquifer region under diffuse recharge conditions (McMahon et al. 2007; Steward et al. 2013). The transit times are in the order of years to several decades even for focused playa recharge (Gurdak et al. 2009). This large time-lag poses significant challenges for integrating watershed and groundwater flow models in this study, as a long hindcast mode simulation run of the watershed model will be necessary to obtain estimates for present day recharge.

Human - Aquifer Interactions

The agrarian economy of the SHP is built on the availability of groundwater. Therefore, human-aquifer interaction, manifested as groundwater production, is the dominant outflow mechanism from the aquifer. Figure 7 shows the county-wide estimates of groundwater use within the model domain. The total groundwater withdrawal in the year 2010 was estimated to be 652,000 hectare-meter (5.29 million acre-feet) over the tristate area of interest (Maupin et al. 2014). Groundwater production exceeds 12,334 hectare-meter (100,000 acre-feet) per year in nearly 30% of the counties within the study area. Groundwater production depicted in Figure 7 correlates strongly with the agricultural land use shown in Figure 1. In addition to agriculture, which accounts for nearly 94% of the total water withdrawals, domestic (0.51%), livestock (1.8%), and urban (2.8%) are other minor but important water use sectors within the study area. The intensive production of groundwater underscores the importance of representing human-aquifer interactions (i.e., extraction rates) in the groundwater model.

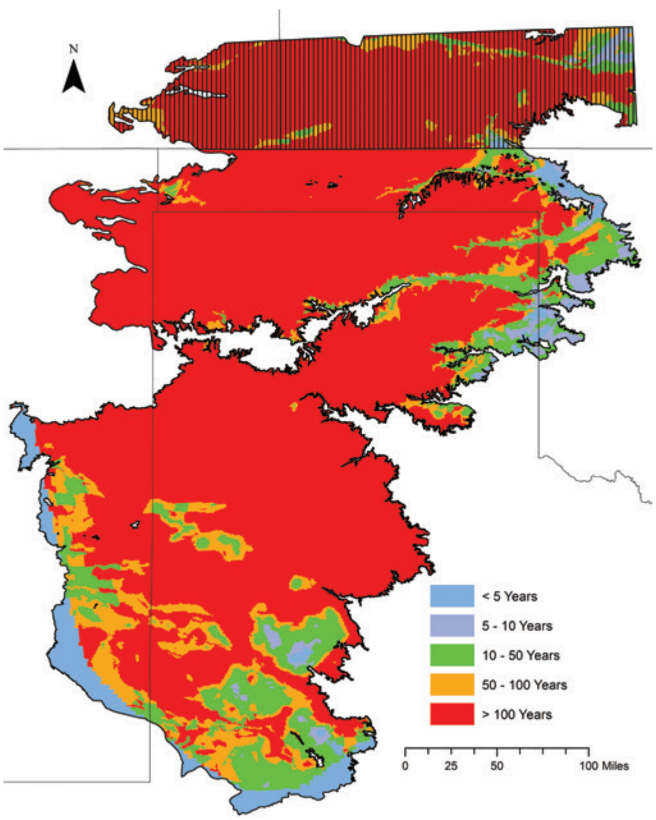

Figure 6. Transit time of wetting front from the bottom of the root zone (3.28 ft (1 m) bgs) to the water table depth corresponding to the year 2013. View color map at: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.

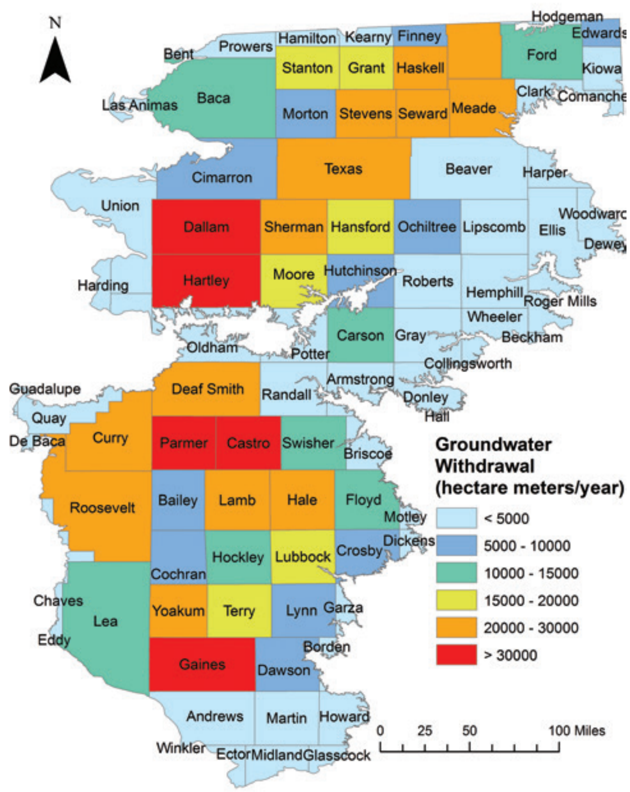

Figure 7. County-wide estimates of total groundwater use within the study area (Data from Maupin et al. 2014). View color map at: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.

Establishing reliable groundwater production estimates is particularly challenging in Texas because of lack of metering of actual use. Oklahoma law authorizes the OWRB to place meters on wells, but only when the majority of landowners overlying the basin request such metering. The metering provision has not been activated in the state of Oklahoma due to the practical difficulty of enforcement as each basin has potentially hundreds of thousands of landowners. The New Mexico office of the State Engineer typically requires meters on wells as part of the permitting process. However, this information is not publicly available at the time of this writing. The lack of directly measured groundwater production data is perhaps the single largest limitation and the greatest source of uncertainty when developing groundwater models in the SHP (Deeds et al. 2015). Indirect approaches to estimate groundwater production become necessary in the absence of direct measurement of groundwater production. On the other hand, uncertainties associated with dominant source/sink terms (i.e., irrigation pumping) can lead to biased estimates of model parameters (Demissie et al. 2015), highlighting the need for reliable estimates for agricultural water production.

Agricultural water production depends on the seasonal crop water requirement which is a function of various meteorological, edaphic, and biological factors. Therefore, in the absence of site-specific information, crop simulation models can assist in providing reasonable estimates for irrigation water requirements. The Decision Support System for Agro-technology Transfer model (DSSAT) (Jones et al. 2003; Hoogenboom et al. 2015) has been adopted here to estimate irrigation water requirements. It has been widely used in the U.S. and in other parts of the world to predict impacts of climate change and evaluate farming methods (Negm et al. 2014; Boote et al. 2017). The DSSAT model has undergone significant development and validation over the last two decades and has the ability to simulate a variety of crops in a phenologically-correct yet parsimonious manner (Hoogenboom et al. 2015). The DSSAT model integrates current theories related to plant growth with a water balance model and nutrient balance models. The model also includes the effects of atmospheric carbon dioxide and as such, is able to simulate future climate states. The DSSAT model also provides ET and irrigation (either full or deficit) water requirements on a daily time-step. It can simulate over forty crops (Hoogenboom et al. 2015) including those grown within the SHP, and can be integrated with geographic information software for spatial comparisons over the study area (Thorp et al. 2008). This data can be appropriately aggregated and used as input to groundwater extractions in agricultural areas.

An illustrative irrigation requirement computed for cotton production around Lubbock, TX is shown in Figure 8 for the years 2010 (a wet year), 2011 (worst single year drought in the recorded history of Texas), and 2012 (a somewhat dry year). The illustrative DSSAT model was developed using cotton cultivar information specific to Texas and soil and climate information corresponding to Lubbock County, TX. Simulations were run using auto-irrigation tools and specifying planting dates typical to the region. While the model was not extensively calibrated against field data, the estimated irrigation water volume computed by the model is within the range of field application rates reported by producers during different simulation years (TAWC 2015), and as such, the parameterization was deemed reasonable for this illustrative application.

The results shown in Figure 8 not only help obtain first-cut estimates for groundwater extractions associated with agricultural production, but also highlight the sensitivity of irrigation water demands to weather patterns during the growing season. Irrigation requirements not only depend upon the amount of annual rainfall, but are also greatly affected by the timing of the rainfall events. Therefore, simulating crop growth at high temporal scale (daily time-step) is necessary to obtain a consistent set of estimates of groundwater production, even when groundwater models are calibrated using coarser monthly or annual stress periods, since the crop water requirement is a function of daily ET. As metered data accounting for groundwater production is absent, a coupling between MODFLOW and a crop model such as DSSAT can be used to obtain reliable estimates for groundwater production, thus reducing uncertainties related to an important MODFLOW input.

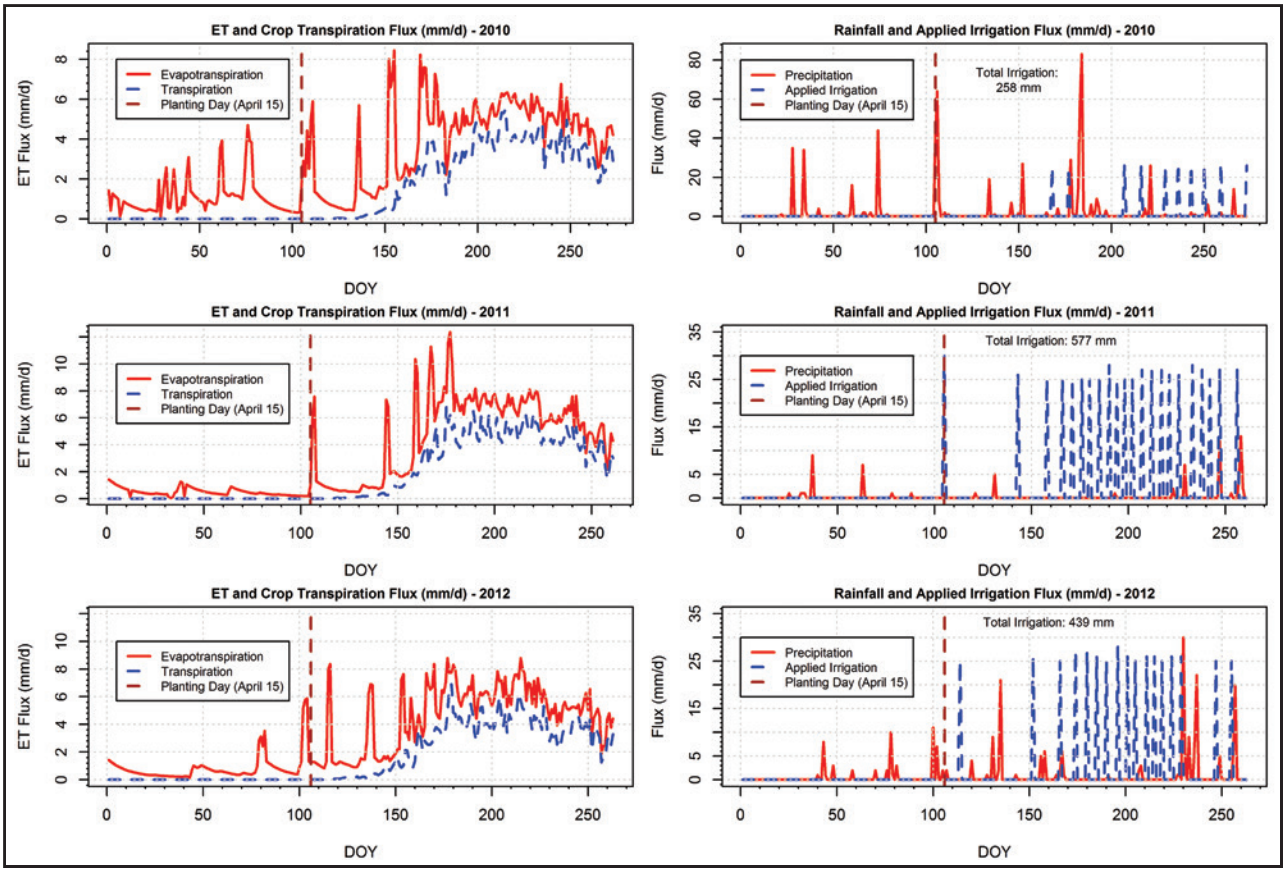

Figure 8. Estimated evapotranspiration and irrigation water requirements for cotton production in Lubbock, TX.

Climate - Aquifer Interactions

The primary driver for current groundwater model development efforts is to help evaluate strategies that prolong the useful life of the Ogallala Aquifer under climate change uncertainties. While climate change impacts on aquifers are not fully understood, increased production of groundwater and reductions in groundwater discharges to surface water bodies (baseflows and spring discharges) are to be expected during periods of drought. However, aquifers act as low pass filters and can attenuate and displace meteorological drought signals (van Lanen and Peters 2000). Therefore, the responses of groundwater can be asynchronous with meteorological droughts. Figure 9 was developed using long-term historical groundwater level and precipitation data. The aquifer impact is assessed by calculating the water level changes between two consecutive annual measurements made during the winter months (i.e., previous year value – current year value) and pairing it with the average lag-12 standard precipitation index (SPI) (McKee et al. 1993), values for the intervening summer months (March-September of the current year). SPI is a widely used index to represent climate states. As to be expected, groundwater declines tend to be greater during droughts (SPI < -0.5), more so than during normal (SPI ± 0.5) and wet states (SPI > 0.5), at some locations, indicating climatic conditions and associated human adaptations propagate through aquifers (see for example, Gaines County, TX; Cimarron County, OK; Bailey County, TX). However, there are also instances where groundwater responses are not statistically different between different climate states (e.g., Texas County, OK; Carson County, TX). In these locations, the aquifer considerably attenuates the effects of climate and can effectively serve as a buffer against droughts. In a few cases, the drawdowns during droughts were noted to be lower than those during wet periods (e.g., Lea

County, NM). This situation typically arises when groundwater resources are well regulated and pumping is significantly curtailed at the onset of droughts.

Recharge is another important parameter that is likely to be affected by changes in climate. Figure 10 depicts the long-term projections of recharge that were estimated using the vadose zone modeling derived power law expression presented in Keese et al. (2005) in conjunction with downscaled climate data for Lubbock, TX (Maurer et al. 2007). The selected models (CCSM 4 and HadGEM2) have been used in other comparative studies (Swain and Hayhoe 2015) and as such, adopted here. The ensemble averages for total annual precipitation projected for the 21st century by both the GCMs were similar to the long-term historical average of around 490 mm (19.29 in). The climate projections from both models indicate that there will be nearly 50% reductions in the estimated mean annual diffuse recharge at this location for all representative concentration pathways. While differences between projected mean recharge are not statistically different across models and pathways, the high emission scenarios generally lead to higher values of recharge than the lower emission scenarios, as they generally contain a larger number of episodic events with higher

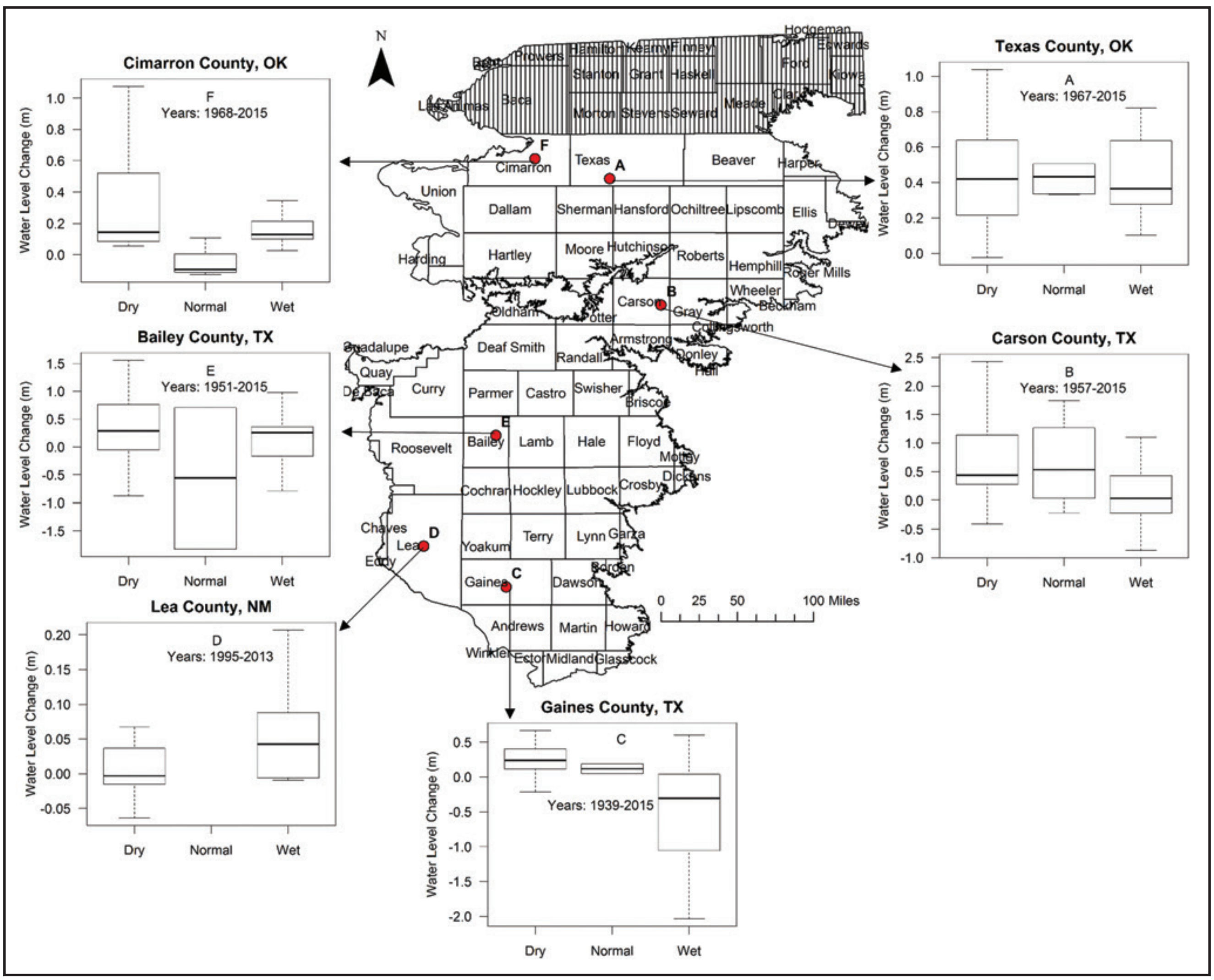

Figure 9. Observed water level changes in the aquifer under different climate states (positive change implies depletion while negative values indicate recovery).

than normal magnitudes. Given the preliminary nature of this analysis and large-scale uncertainties associated with climate models, the estimated recharge time-series should not be viewed as definitive and should only be interpreted in a broad sense. The result suggests that careful attention must be paid to develop recharge estimates when the calibrated groundwater model is run in a predictive mode to support water resources planning studies, as the estimates are driven by the uncertainty in GCMs.

The idea of coupling vadose zone modeling simulator – HYDRUS 1D, (Simunek et al. 2008) and/or coupled SWAT-HYDRUS model with long-term downscaled precipitation data can be helpful to develop refined estimates of future recharge when applying groundwater models in climate-oriented future policy planning studies, where long-term (multi-decadal to century scale) projections have to be made. HYDRUS based models that are temporally detailed can provide critical feedback about the episodic nature of potential future recharge for the groundwater models. Therefore, recognizing that the recharge is episodic and critically depends upon the timing of precipitation events warrants a high-resolution time stepping of the groundwater flow model to better capture rainfall-recharge dynamics. Vadose

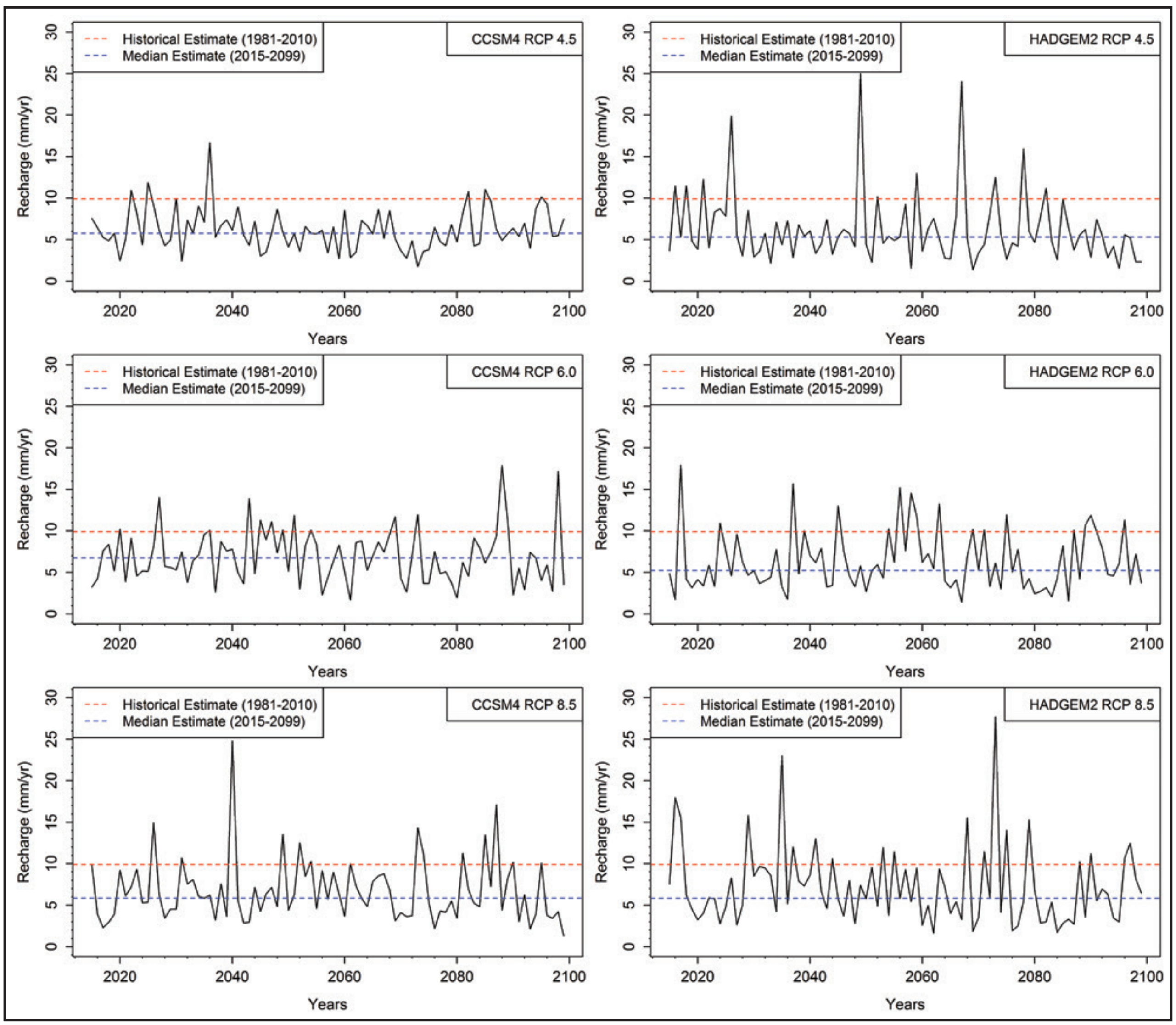

Figure 10. Estimated diffuse annual recharge at Lubbock, TX using the power-law expression of Keese et al. (2003).

zone flow simulation packages for MODFLOW groundwater flow model have been presented in the literature and may be useful in this regard (Niswonger et al. 2006; Twarakavi et al. 2008).

Summary and Conclusions

Groundwater modeling requires that boundary conditions through which the modeled aquifer system interacts with the atmosphere, land, climate, and human sub-systems must be properly parameterized. Existing groundwater flow simulators, such as MODFLOW, provide rudimentary approaches to account for climate-hydrologic-human interactions with aquifers. Improper parameterization or conceptualization of these interactions create issues with model calibration and may lead to erroneous or physically unrealistic results. In most cases, fluxes across the boundaries must be explicitly specified as closure conditions. The integration of climate, watershed, vadose zone, crop growth, and social dynamic models with groundwater simulators are being undertaken to increase the fidelity of interaction between the aquifer and its boundaries. These model couplings also are helpful to estimate missing data and explicitly model how changes in one system (say land use) affect the conditions in the aquifer. It is important to note that integrated modeling also greatly increases the data requirements. For example, if SWAT and MODFLOW models are integrated to estimate recharge, the watershed model (SWAT) must be properly parameterized and even in simple cases will require tens of model inputs. The benefits of integration versus the costs of parameterizing the model must be carefully evaluated. It is recommended that a comprehensive evaluation of integrated modeling approaches to better parameterize climate-hydrologic-human interactions be included as part of the groundwater conceptual modeling exercise.

The present study presents several "first-cut" engineering analysis methods to guide integrated modeling assessment and demonstrates their utility using an on-going groundwater model development study for the Ogallala Aquifer in the SHP region of Texas, New Mexico, and Oklahoma. The results obtained here indicate that surface water-groundwater interactions have greatly diminished over the last six decades within the study area due to dwindling groundwater levels, indicating that simple parameterization of surface water-groundwater fluxes is likely sufficient. Available estimates for recharge vary widely and to a large degree are controlled by the "playas" in the region. As the deep percolation transit times through the vadose zone are very long over most of the study area, coupling of SWAT or similar watershed models with groundwater flow simulators may not be warranted except perhaps for multi-decadal simulations. While the area relies heavily on groundwater, direct metering of groundwater pumping has not been undertaken over most of the model domain. Agriculture accounts for nearly 95% of the groundwater withdrawals in the region. As such, crop growth models such as the DSSAT can be extremely helpful to generate reliable estimates for irrigation water use as they model a large variety of crops grown in the SHP region, and can be integrated using GIS to cover large spatial extent. The coupling of the DSSAT with MODFLOW can help guide future land use informed groundwater policy planning endeavors, as well. The coupling between the DSSAT and MODFLOW is currently being researched and hence has not been discussed in detail in this manuscript.

Understanding how aquifers respond and behave under different climate states is important when groundwater models are to be used for future policy planning and management efforts. The historically observed response of the Ogallala Aquifer to different climate states during the growing season was seen to exhibit considerable variability. However, the changes in water levels between consecutive years exhibited greater variability and generally exhibited bigger depletions during droughts than during periods of higher rainfalls. Some parts of the aquifer appeared well buffered against climate states. Projecting future recharge is necessary for climate-informed groundwater policy planning efforts. Initial analysis presented here indicates annual diffuse recharge flux will likely decrease in the 21st century despite long-term precipitation levels showing no change. However, additional analysis, especially accounting for variations in soil and properly characterizing the timing of rainfall events, is necessary to establish a better picture. As transit times through the vadose zone are large, multi-decadal simulations with vadose zone models coupled with groundwater simulators may be useful to better characterize and simulate rainfall-recharge dynamics in climate change studies.

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The Economics of Local Enhanced Management Areas in Southwest Kansas

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Abstract: The purpose of this research is to provide input into the water planning process for select subareas in southwest Kansas. Stakeholder input suggests that a reduction in groundwater use may be desirable in order to preserve the Ogallala Aquifer and extend its economic contribution to both the producer and the regional economy. In an endeavor to define the benefits and costs of water conservation policy, this research estimates measures of producer net profits and regional value added and places a monetary value on the conserved groundwater. The results of the models that assume the goal is to maximize producer profits, suggest that the Local Enhanced Management Areas (LEMAs) framework of groundwater management will provide benefits to both the agricultural producer and rural communities. Subarea 1 will receive the greatest benefit, increasing cumulative net revenue by 6.3%, while Subareas 2 and 3 increase cumulative net revenue by 2.1% and 2.7%, respectively. The results suggest that generally, the rural economy receives as much, if not more, benefits from groundwater conservation than the agricultural producer. Subareas 1, 2, and 3 generated 8.3%, 2.7%, and 1.8%, respectively, more cumulative value added under the LEMA scenario as compared to the Status Quo scenario. If Subarea 3 were to manage their groundwater based on implementing a LEMA plan and maximizing value added, cumulative value added would increase from a 1.8% gain to an increase of 18.7%.

Keywords: *groundwater, net present value, Ogallala Aquifer, value added, water conservation*

Groundwater consumption in southwest Kansas far exceeds the amount of recharge in the Ogallala Aquifer. This raises concerns relative to the long-term feasibility of irrigated agriculture in the area and the industries that rely on it. The depletion of the Ogallala Aquifer in this area will have serious negative economic impacts on agricultural producer profits and the associated value-added of the regional economy. In order to extend the economic life of the aquifer and maintain the economic base of the region, policy intervention may need to be considered.

Past efforts to slow the decline and ensure the future economic viability of the region have been largely unsuccessful (Peterson et al. 2003; Griggs 2014). The 2012 Kansas Legislature passed Senate Bill (SB) 310 making Local Enhanced Management Areas (LEMAs) a part of Kansas water law. This law gives groundwater management districts (GMDs) the authority to initiate a voluntary public hearing process to consider a specific conservation plan to meet local goals. LEMAs are proactive, locally designed, and initiate water management strategies for specific geographic areas that are promoted through a GMD and then reviewed and approved by the Chief Engineer. Once approved by the Chief Engineer, the LEMA plan becomes law, effectively modifying prior appropriation regulations. The stated purpose of the LEMA legislation was to reduce groundwater consumption in order to conserve the state's water supply and extend the life of the Ogallala Aquifer.

The objective of this study is to provide assistance to the stakeholders in GMD#3 in their water planning process. This report documents the methods, assumptions, and estimates of the likely economic impacts associated with the implementation of LEMAs in three high priority subareas located within GMD#3 as illustrated in Figure 1. Various hydrological parameters associated with the subareas are reported in Table 1. This analysis compares a Status Quo scenario to a LEMA scenario for each of the three subareas. The Status Quo scenario assumes that there is no change in groundwater use behavior and producers keep pumping all wells into the future based on historic pumping. Based on input from the stakeholders, the LEMA scenario assumes there is an immediate 20% reduction, based on historic pumping. Both scenarios are simulated under normal or average climatic conditions. Note that the term 'water use' throughout this article takes the meaning of 'consumptive water use'.

Methodology

Economic models that forecast future conditions are subject to error, and the results are generally viewed as only one possible prediction. From a policy analysis perspective, it is not necessary that the individual scenario predictions be perfectly accurate; it is important to focus on the 'difference' between scenarios. As long as consistency is maintained, and stakeholders agree with the methodology and assumptions, comparisons of different scenarios are appropriate to evaluate groundwater management options.

This study relies heavily on models previously developed by Golden and Johnson (2013) which provides a very detailed model description. The study requires the development of two broad classes of economic models. The temporal allocation portion of the model is linked with a hydrological model previously developed by the Kansas Geological Service (KGS), and provides the required time series forecast on groundwater use, irrigated acreage, and economic productivity for the Status Quo and LEMA scenarios. The models of regional economic impact utilize the output from the temporal allocation models to predict the economic value added for the two scenarios. The model is illustrated in Figure 2.

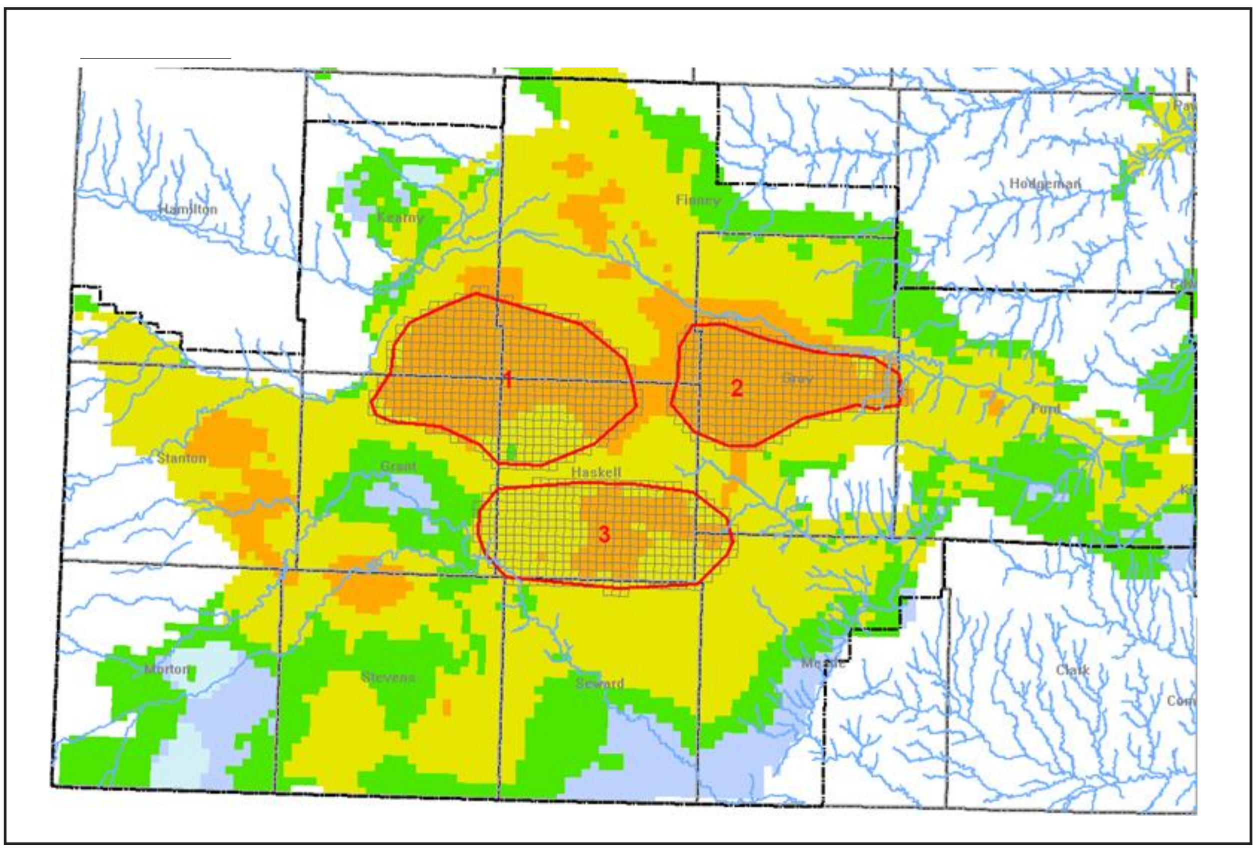

Figure 1. Three high priority subareas located in Groundwater Management District 3 in Kansas.

Table 1. Subarea hydrological parameters.

Item	High Priority Area 1	High Priority Area 2	High Priority Area 3
Recharge (inches/year)	1.94	2.24	1.01
Depth to Water (feet)	227.93	145.22	268.58
Saturated Thickness (feet)	222.55	120.43	227.37
Hydraulic Conductivity (feet/day)	43.64	53.06	46.29
Specific Yield	0.17	0.17	0.18
Average Well Capacity (gallons per minute)	633.19	489.74	665.31
Average Decline in Saturated Thickness (feet)	2.98	2.44	2.28
Average Water Use per Acre (feet)	1.45	1.32	1.13
Average Annual Water Use (acre-feet)	178,284.60	115,994.60	145,964.00

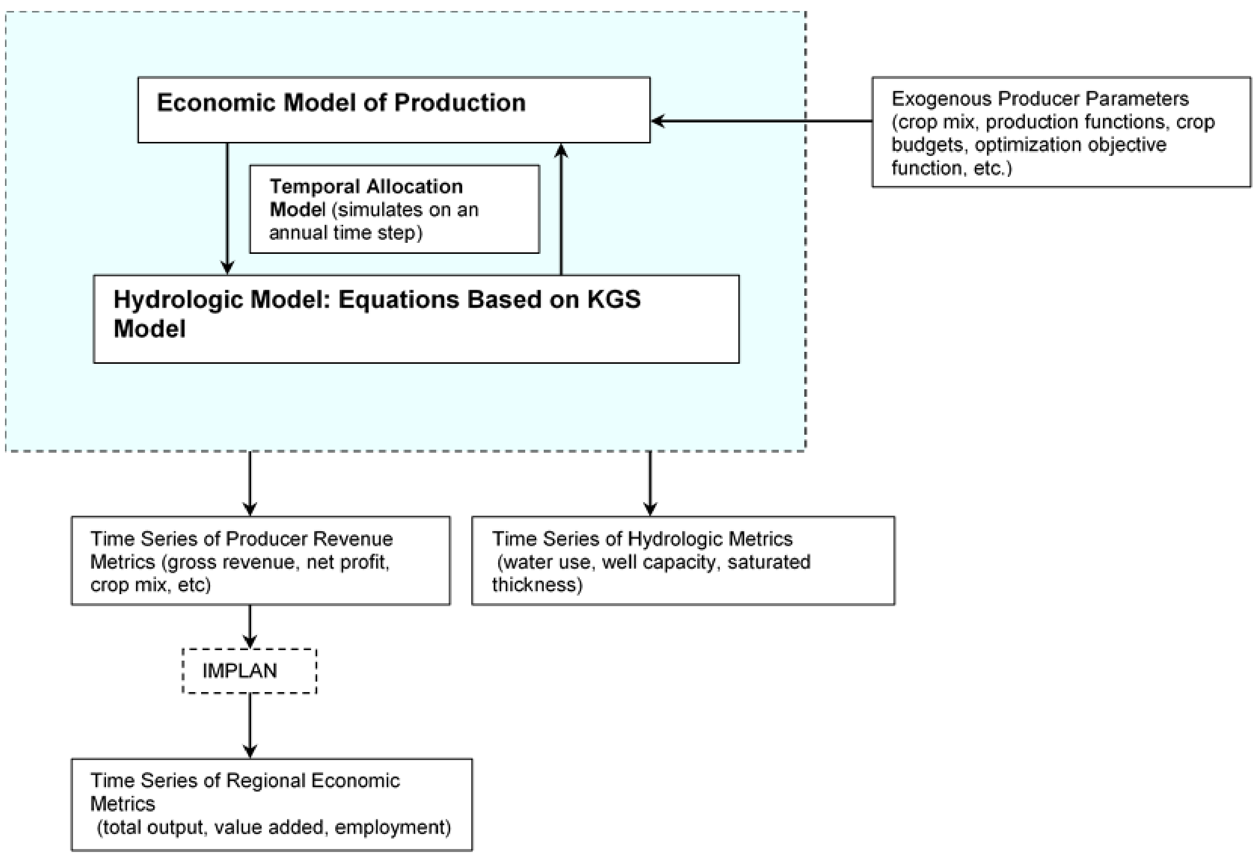

Figure 2. Regional economic impact model.

The producer's annual objective function for the dynamic simulation model is normally based on the concept that an agricultural producer will maximize profits (Amosson et al. 2009; Golden and Johnson 2013). This objective function implicitly assumes that what is best for the producer is also best for the rural economy. The annual profit maximizing objective function can be defined as:

$$\max_{A,w} \sum_{i=1}^{n} P_i Y_{i,t}(w_{i,t})A_{i,t} - C_{i,t}(w_{i,t})A_{i,t}$$

$$s.t.\ \sum_{i=1}^{n} w_{i,t} A_{i,t} = TW_{KGS,t}$$

$$s.t.\ ST_t = ST_{KGS,t}$$

$$s.t.\ \sum_{i=1}^{n} A_{i,t} = TA \qquad (1)$$

where $w_{i,t}$ is the water allocation for crop i in time period t; $A_{i,t}$ is the acreage allocation for crop i in time period t; $Y_{i,t}$, a function of $w_{i,t}$, is the per acre yield for crop i in time period t; $C_{i,t}$, a function of $w_{i,t}$, is the per acre cost for crop i in time period t; and P_i is the per unit price of crop i. The previously described equation is maximized subject to (s.t.) several constraints. The model is simulated on an annual basis for a period of t = 1… 61 years. Golden and Johnson (2013) reported the prices and costs for irrigated and non-irrigated crop production used in this analysis.

The typical single cell aquifer model and the associated equations of motion for saturated thickness, annual water use, and well capacity have been replaced by hydrologic equations of motion. These equations are based on regression analysis of the output of the KGS Model utilized by Golden and Johnson (2013). The first two constraints state that model-generated total water use (*TW*) and saturated thickness (*ST*) at any point in time has to be equal to a previously determined total groundwater use and saturated thickness as provided by the KGS Model.

The third constraint implies that total acreage (*TA*) cannot change over time. This model only considers the current irrigated acreage in the subareas. The model predicts how irrigated crop mix might change over time due to declining groundwater availability. The current irrigated crop mix and the average per acre water use for these crops for each of the subareas are reported in Table 2 and Table 3, respectively. The model also forecasts when irrigated acreage will shift to dryland production. As irrigated acreage converts to dryland it is assumed these acres will shift to the crop mix reported in Table 4. The percent pasture is based on the percentage of land that falls into Natural Resources Conservation Service (NRCS) Class 5 soils or greater[1] (Table 4). For this analysis, the net returns associated with pasture are assumed to be $10.00 per acre and the costs associated with fallowed land are assumed to be $30.00 per acre.

Models of Regional Economic Impact

When agricultural groundwater use is restricted, either from policy intervention or declining well capacity, crop production will, in all likelihood, be reduced in the near term and producers and local communities will incur negative economic impacts. The magnitude of the reduction in crop yields will depend upon the magnitude of the groundwater use reductions, the current level of groundwater use efficiency in the production process, the number of acres involved, the crop mix for the area, crop yields (which are dependent on crop-specific production functions, impacted by local precipitation and temperature), prices and costs, and the relative economic importance of agriculture to the affected communities. The direct impacts (changes in gross revenue) estimated by the temporal allocation models, for various scenarios, are used as input for the regional economic impact models. IMpact analysis for PLANning (IMPLAN) software is used to quantify the indirect and induced economic impacts to the regional economy (IMPLAN Group, LLC 2009).

The most relevant measure of the local economic impact may be 'value added'. Value added consists of four components: 1) employment compensation (wage, salary, and benefits paid by the employers); 2) proprietor income (payments received by self-employed individuals as income); 3) other property income (payments to individuals in the form of rents); and 4) indirect business taxes (basically

1 Per the NRCS handbook available at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/soils/?cid=nrcs142p2_054226: Class V (5) soils have little or no hazard of erosion but have other limitations, impractical to remove, that limit their use mainly to pasture, range, forestland, or wildlife food and cover.

Table 2. High priority subarea irrigated crop mix.*

High Priority Subarea	Alfalfa	Corn	Sorghum	Soybeans	Wheat
1	38.9%	49.7%	1.6%	4.3%	5.4%
2	35.5%	43.5%	2.5%	6.0%	12.2%
3	3.8%	83.1%	2.8%	3.3%	6.5%

*Based on average data (2000-2009) obtained from the Water Right Information System (WRIS) database.

Table 3. High priority subarea current average use (acre-inches).*

High Priority Subarea	Alfalfa	Corn	Sorghum	Soybeans	Wheat
1	21.7	19.6	12.0	18.3	12.2
2	20.0	18.3	9.9	15.9	7.2
3	18.4	17.6	11.8	13.1	9.2

*Based on average data (2000-2009) obtained from the Water Right Information System (WRIS) database.

Table 4. High priority subarea projected dryland crop mix.*

High Priority Subarea	Corn	Sorghum	Wheat	Fallow	Pasture**
1	4.2%	13.1%	28.3%	15.2%	39.4%
2	3.0%	9.5%	20.4%	11.0%	56.2%
3	6.6%	20.6%	44.6%	23.9%	4.3%

* The percentage of acreage for corn, sorghum, wheat, and fallow is based on NASS averages for CRD 30 (1999-2009).

**The percent pasture is based on the percentage of land that falls into NRCS Class 5 soils or greater.

all taxes with the exception of income tax) (IMPLAN Group, LLC 2009). Thorvaldson and Prichett (2007) and BBC Research & Consulting et al. (1996) suggest that value added is the most appropriate measure of community economic impact. This research reports the measure of value added and uses the metric to compare policy options. The value added multipliers used in this analysis are reported in Table 5.

Net Present Value Analysis

Net present value comparison is a standard method used to compare long-term projects. The calculation discounts future cash flows to present values and sums the resulting income stream. Net present value calculations require a 'discount rate' that transforms future values into present values. The use of a positive discount rate would imply the conventional view, that profits today are more valuable than profits in the future. A positive discount rate might be chosen by a producer that focuses on the near term cash flows necessary to meet current obligations such as land and equipment payments. A zero percent discount rate would imply neutrality as to the timing of cash flows. The use of a negative discount rate would imply that profits, and by extension water, is valued more highly in the future than it is today. Such a stance might be taken by a producer that wants to ensure that water resources are conserved today so that his children might enjoy the stability of irrigated production in the future. Consistent with Golden and Johnson (2013), this analysis uses a zero percent discount rate to make non-bias comparisons between policy

Table 5. Value-added multipliers for irrigated and non-irrigated crops in Southwest Kansas.

	Direct	Indirect	Induced	Total
Irrigated	0.37	0.13	0.11	0.61
Non-Irrigated	0.50	0.11	0.15	0.75

alternatives. A comparison of alternative discount rates utilized in this type of analysis can be found in Vestal et al. (2017).

The Value of Groundwater

It is straight-forward to compare the scenario differences in variables such as producer revenues, well capacity, and saturated thickness. However, a policy such as the LEMA Model restricts water use relative to a Status Quo scenario and over the 61-year time frame generally results in less total groundwater consumed. In most temporal allocation studies, economists rarely estimate the value of the remaining conserved groundwater (Golden et al. 2008; Amosson et al. 2009). This may be because from a purely production standpoint, groundwater has no value until it is brought to the surface and used and it is uncertain what it may be used for in the future. Additionally, studies that discount future values (positive discount rates) may find that any remaining water in the future (after 61 years) has negligible value today. Amosson et al. (2017) suggest that the cost of generating water savings must be weighed against the benefit of doing so and to accomplish this, a 'price tag' needs to be given to the water that is conserved.

Golden and Johnson (2013) valued the conserved groundwater based on the difference in the non-discounted cumulative net returns, over the 61-year modeling period, divided by the cumulative groundwater use, over the 61-year modeling period. This metric yielded an average value of groundwater over the 61-year modeling period. While this method was consistent with stakeholder input at the time, more recent input from reviewers and stakeholders suggests that using the average method undervalues conserved groundwater if growth in crop yield is assumed. This analysis assumes that the value of conserved groundwater is the difference in the non-discounted cumulative net returns, during the 61st year of the modeling period, divided by the cumulative groundwater use, during the 61st year of the modeling period.

Growth in Crop Yield

For several decades there have been significant adoptions of new crop varieties and cultural practices. The more recent adoption of biotechnology has allowed producers to increase yields and decrease input use. When projecting groundwater use into the future, it is important to include estimates of the growth in crop yields. Amosson et al. (2009) assumed all irrigated crop yields increase at the rate of 0.5% per year. Golden and Johnson (2013) assumed that irrigated crop revenues increase at 0.5% per year relative to non-irrigated crop revenues.

Rogers and Lamm (2012) provide data on the long-term growth rate of the major irrigated crops in Kansas. The interpolation of these data is reported in Table 6. There is little economic research quantifying how various factors (cultural practices, genetics, water availability, etc.) are impacting the growth rates, so it is unclear if the growth rate should be expected to increase or decrease into the future. As a result, this research utilizes conservative estimates of future growth rates at 50% of those values interpolated from Rogers and Lamm (2012).

Results and Discussion

Typically, a Status Quo scenario is constructed that represents a baseline and assumes unconstrained producer behavior. A second scenario is constructed that represents the exogenous impact of a policy option which imposes a constraint on producer behavior. In this study, the implementation of a LEMA, which reduces current groundwater use by 20%, is the imposed constraint. Since there is an immediate reduction in groundwater usage of 20%, declines in saturated

Table 6. Estimates of future crop yield growth.

Crop	Estimated Growth Rate	Conservative Growth Rate
Irrigated Alfalfa	0.00%	0.00%
Irrigated Corn	1.31%	0.66%
Irrigated Sorghum	0.54%	0.27%
Irrigated Soybeans	0.95%	0.47%
Irrigated Wheat	0.64%	0.32%
Dryland	0.51%	0.25%

thickness are slowed, and future pumping capacity is increased. As a result, more groundwater is available to be used in the future in the LEMA scenario when compared to the Status Quo scenario. The impact of this is that the cumulative groundwater use for the LEMA scenario will be less than 20% relative to the Status Quo scenario (Figure 3). Since less groundwater is used in the short-term under the LEMA scenario, annual crop yields and net revenues are also reduced. In the long-run, however, the LEMA scenario uses more groundwater in the latter years of the study when crop yields are higher due to technological growth, and as a result, overall net revenue is increased (Figure 4). The time series results of the two dynamic simulation models are then compared to assess the impact of the exogenous shock.

The cumulative groundwater use for the Status Quo and LEMA scenarios for Subarea 1 is reported in Table 7. The LEMA scenario uses approximately 9.5% less groundwater over the 61-year modeling horizon, and adds approximately 9.5 years (15.4% more time) relative to the groundwater use associated with the Status Quo scenario. The LEMA scenario results in 6.3% more cumulative net revenue (Table 8) and a gain of 8.3% in cumulative value-added (Table 9).

The cumulative groundwater use for the Status Quo and LEMA scenarios for Subarea 2 is reported in Table 10. The LEMA scenario uses approximately 0.1% less groundwater over the 61-year modeling horizon, and adds less than a year, relative to the groundwater use associated with the Status Quo scenario. The LEMA scenario results in 2.1% more cumulative net revenue (Table 11) and a gain of 2.7% in cumulative value-added (Table 12).

The cumulative groundwater use for the Status Quo and LEMA scenarios for Subarea 3 is reported in Table 13. The LEMA scenario uses approximately 4.1% less groundwater over the 61-year modeling horizon, and adds approximately 4.8 years (7.9% more time) relative to the groundwater use associated with the Status Quo scenario. The LEMA scenario results in 2.7% more cumulative net revenue (Table 14) and a gain of 1.8% in cumulative value-added (Table 15).

Kansas administers groundwater rights based on a *prior appropriation* doctrine. This implies that all the groundwater is owned by the state and dedicated to the use of the citizens as specified in the state's water appropriation act (K.S.A. 82a-701). This law is designed to protect both the land owners' right to use groundwater today as well as protect the supply of groundwater for future generations. K.S.A. 82a-702 states that "all water within the state of Kansas is hereby dedicated to the use of the people of the state, subject to the control and regulation of the state in the manner herein prescribed." This might imply that groundwater management, to some extent, be based on what is most beneficial to rural communities. As previously stated, dynamic simulation models have historically been based on the assumption that an agricultural producer will maximize profits, which implicitly assumes that groundwater management should be based solely on what is best for the agricultural producer. As an alternative, dynamic simulation models were developed which are based on the assumption that the goal is to maximize value added generated in the rural economy. This implicitly assumes

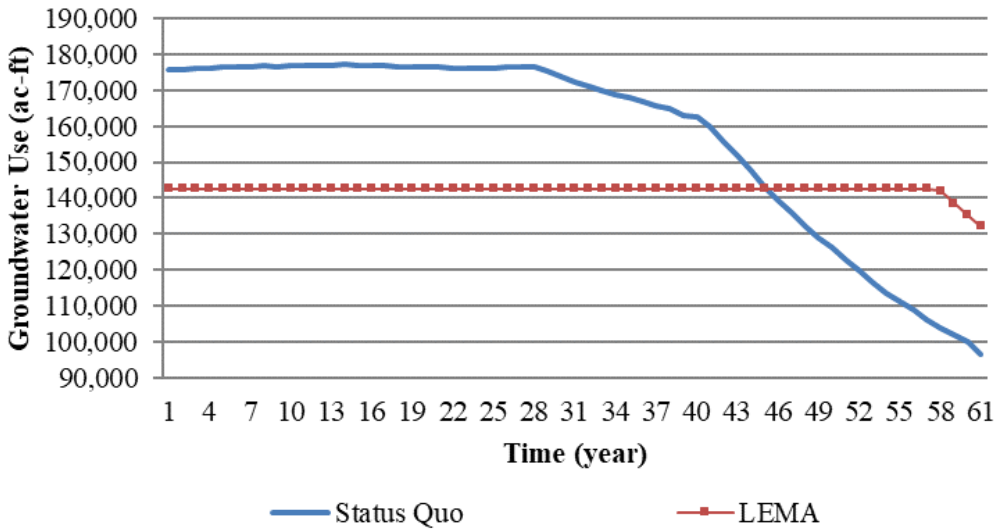

Figure 3. Cumulative groundwater use for Subarea 1.

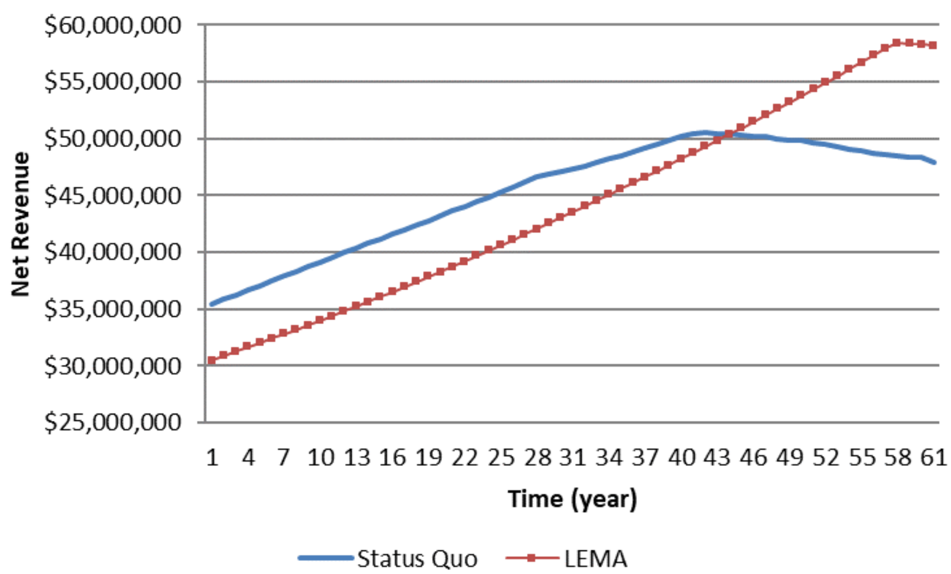

Figure 4. Cumulative producer net revenue from crop production for Subarea 1.

that groundwater management is based solely on what is best for the rural community. Results from this alternative dynamic simulation model are presented below.

Utilizing the dynamic simulation model which assumes that the objective function is to maximize the rural communities' value added, the cumulative groundwater use for the Status Quo and LEMA scenarios for Subarea 3 over the 61-year modeling horizon is reported in Table 16. The LEMA scenario uses approximately 4.1% less groundwater over the 61-year modeling horizon, and adds approximately 4.8 years (7.9% more time) relative to the groundwater use associated with the Status Quo scenario. The LEMA scenario results in 0.0% more cumulative net revenue (Table 17) and a gain of 18.7% in cumulative value-added (Table 18).

The results of the models, that assume the goal is to maximize producer profits, suggest that the LEMA framework of groundwater management will provide benefits to both the agricultural

Table 7. Cumulative groundwater use for **Subarea 1** (acre-feet).

Scenario	Cumulative Groundwater Use	Relative Groundwater Use
Status Quo	9,583,338	0
LEMA	8,677,622	-905,716

Table 8. Cumulative producer net revenue ($ millions) for **Subarea 1.**

Scenario	Cumulative Net Revenue	Relative Net Revenue	Value of Remaining Water	Net
Status Quo	$2,767.8	$0	$0	$2,767.8
LEMA	$2,691.1	-$76.7	$328.2	$2,942.6

Table 9. Cumulative value added ($ millions) for **Subarea 1.**

Scenario	Cumulative Total Value Added	Relative Value Added	Value of Remaining Water	Net
Status Quo	$4,926.0	$0	$0	$4,926.0
LEMA	$4,821.4	-$104.6	$618.1	$5,335.0

Table 10. Cumulative groundwater use for **Subarea 2** (acre-feet).

Scenario	Cumulative Groundwater Use	Relative Groundwater Use
Status Quo	4,692,522	0
LEMA	4,687,627	-4,894

Table 11. Cumulative producer net revenue ($ millions) for **Subarea 2.**

Scenario	Cumulative Net Revenue	Relative Net Revenue	Value of Remaining Water	Net
Status Quo	$1,586.9	$0	$0	$1,586.9
LEMA	$1,602.1	$15.2	$2.7	$1,620.1

Table 12. Cumulative value added ($ millions) for **Subarea 2.**

Scenario	Cumulative Total Value Added	Relative Value Added	Value of Remaining Water	Net
Status Quo	$2,782.2	$0	$0	$2,782.2
LEMA	$2,817.0	$34.7	$4.8	$2,856.4

Table 13. Cumulative groundwater use for **Subarea 3** (acre-feet).

Scenario	Cumulative Groundwater Use	Relative Groundwater Use
Status Quo	7,164,649	0
LEMA	6,874,580	-290,070

Table 14. Cumulative producer net revenue ($ millions) for **Subarea 3.**

Scenario	Cumulative Net Revenue	Relative Net Revenue	Value of Remaining Water	Net
Status Quo	$2,287.2	$0	$0	$2,287.2
LEMA	$2,257.4	-$29.8	$121.5	$2,349.1

Table 15. Cumulative value added ($ millions) for **Subarea 3.**

Scenario	Cumulative Total Value Added	Relative Value Added	Value of Remaining Water	Net
Status Quo	$4,326.2	$0	$0	$4,326.2
LEMA	$4,159.2	-$166.9	$255.6	$4,248.0

Table 16. Cumulative groundwater use for **Subarea 3** (acre-feet) (VA as the Objective Function).

Scenario	Cumulative Groundwater Use	Relative Groundwater Use
Status Quo	7,164,649	0
LEMA	6,877,179	-287,471

Table 17. Cumulative producer net revenue ($ millions) for **Subarea 3** (VA as the Objective Function).

Scenario	Cumulative Net Revenue	Relative Net Revenue	Value of Remaining Water	Net
Status Quo	$2,287.2	$0	$0	$2,287.2
LEMA	$2,226.7	-$60.5	$120.2	$2,226.7

Table 18. Cumulative value added ($ millions) for **Subarea 3** (VA as the Objective Function).

Scenario	Cumulative Total Value Added	Relative Value Added	Value of Remaining Water	Net
Status Quo	$4,326.2	$0	$0	$4,326.2
LEMA	$4,597.6	$271.4	$268.1	$5,137.0

producer and the rural communities. The magnitude of these benefits varies by subarea. Subarea 1 will receive the greatest benefit with an increase in cumulative net revenue of 6.3%, while Subareas 2 and 3 are expected to have increases in cumulative net revenue of 2.1% and 2.7%, respectively. The variation in subarea specific results are due to variations in initial hydrological conditions, current and projected irrigated crop mix, and dryland production options, which determine how the irrigated crop mix varies over time and the rate at which irrigated cropland is converted to dryland production.

Consistent with Golden and Johnson (2013), this research suggests that the rural economy receives as much, if not more, benefit from groundwater conservation as does the agricultural producer. Subarea 1, Subarea 2, and Subarea 3 generated 8.3%, 2.7%, and 1.8%, respectively, more cumulative value added under the LEMA scenario as compared to the Status Quo scenario. These findings raise the question as to the extent to which value added could be increased if groundwater was managed based on maximizing value added as opposed to maximizing producer profits. If Subarea 3 were to manage their groundwater based on implementing a LEMA and maximizing value added, cumulative value added would increase from a 1.8% gain to an increase of 18.7%. While an in-depth analysis of how this concept would impact other areas in southwest Kansas, and how we might implement such a policy, goes beyond the scope of this research, the topic certainly requires future research.

Conclusions

The purpose of this research was to provide input into the water planning process for select subareas in southwest Kansas. The study considered two groundwater use scenarios, a Status Quo scenario and a LEMA scenario. Stakeholder input suggests that a reduction in groundwater use may be desirable in order to conserve the Ogallala Aquifer and extend its economic contribution to both the producer and the regional economy. This research estimates measures of cumulative producer net profits and regional value added in order to estimate the benefits and costs of the LEMA water conservation policy. This research placed a monetary value on the conserved groundwater and considers a future where continued growth in irrigated crop yields is assumed.

In order to accomplish the goals of this research, previously developed economic and hydrological models were modified and used to estimate impacts over a 61-year time horizon. Since the development of economic models for predicting the future is, by its very nature subject to error, the results of such models are most appropriately viewed as a ‘best guess’. The estimated impacts were based on a variety of assumptions. A different set of assumptions will alter the magnitude of impacts. So long as consistency of assumptions is maintained across policy options, different assumptions may not impact the relative order of policy choices.

While the results are sensitive to assumptions regarding the future value of groundwater and crop yield growth, they suggest that LEMA groundwater use restrictions may lead to economic benefits for both the producer and rural economies. The variation in subarea specific results is due to differences in initial hydrological conditions and dryland production options which determine how the irrigated crop mix varies over time and the rate at which irrigated cropland is converted to dryland production.

The adoption of a LEMA as a water conservation policy may reduce groundwater consumption in the short-run but will not reduce groundwater consumption over an infinite horizon. Even with rather severe reductions in groundwater use today, the subareas will remain over-appropriated and water saved today will eventually be used and the water resource exhausted.

This research is based on a LEMA that imposes a 20% water use restriction. A 20% water use restriction may not be appropriate for all areas of southwest Kansas. This research did not attempt to find the magnitude of a water use restriction which maximized cumulative net producer profit over the 61-year time horizon. Additional research is needed to define those values.

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Water Budget Development for SGMA Compliance, Case Study: Ukiah Valley Groundwater Basin

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Abstract: The Sustainable Groundwater Management Act (SGMA) is the first comprehensive legislative effort to reform groundwater management in the state of California after years of uncoordinated and voluntary governance of this resource. The objective of this study is to a) describe the SGMA in California, b) describe a method for estimating a water budget, and c) present the implementation of this method for the Ukiah Valley Groundwater Basin (UVGB). An estimated water budget, done on a monthly time step from 1991 to 2015, was developed in order to characterize the UVGB. Results suggest that the groundwater basin is not in overdraft, and that a portion of the Russian River is a gaining river (approximately 18,952 AF/y) from November to June, and a losing river (approximately 393 AF/y) from July to October. Furthermore, lateral groundwater movement is identified through the groundwater mass balance. Based on previous work and the results of this study, the observed later groundwater losses signify connectivity between the UVGB and the Sanel Valley Groundwater Basin (SVGB). Local groundwater managers and users can use this information to inform proposed action plans and monitoring protocols that will allow them to achieve and maintain groundwater sustainability in the UVGB by the year 2040.

Keywords: *groundwater budget, California, groundwater management, SGMA, water budget, sustainability, water management, water resources management*

Prior to 2014, California did not have a comprehensive plan for managing its groundwater resources. It was not until 2014 that the Sustainable Groundwater Management Act (SGMA) was adopted in California. The SGMA aims to promote groundwater sustainability by preventing these six undesirable conditions: 1) chronic lowering of the water table resulting from the depletion of groundwater storage; 2) groundwater overdraft; 3) reduction in stream flows due to groundwater-surface water disconnections; 4) groundwater quality degradation; 5) land subsidence; and 6) salt water intrusion into groundwater basins (Lund and Harter 2013). The present study introduces a water budget method that helps groundwater managers create some, but not all, necessary baseline measures from which to develop a Groundwater Sustainability Plan (GSP) so as to achieve groundwater sustainability in areas required to comply with the SGMA. More information on this method can be found in Flores Marquez (2017). This proposed method accounts primarily for water accounting and does not address the following three undesirable effects of SGMA: 1) groundwater quality degradation, 2) land subsidence, and 3) salt water intrusion into the groundwater basin.

Water budgets are a helpful evaluation tool for effective water resources management and environmental planning. A water budget utilizes the continuity equation to account for all water that flows in and out of a control volume, resulting in a change in storage. All of the groundwater and surface water that enters and leaves the system is accounted for in this process and ultimately accounts for any change in water storage over time. A water budget evaluates the availability and sustainability of water supplies and provides a simple way to assess the impacts of climate change and human influence on water resources (Healy et al. 2007). Water budgets have previously been done for groundwater basins in California (Ruud et al. 2002; Foglia et al. 2013; DWR 2016). Some water budgets have been created with programs such as the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) and the Integrated Water Flow Model (IWFM, that consider surface water and groundwater) or the Soil and Water Assessment Tool (SWAT, a program capable of doing water balances in the root zone). The water budget method proposed in this study is unique among these because it estimates a surface water balance while explicitly considering each individual water user, as opposed to lumping all of them together as one larger surface water user (C2VSIM, IWFM, and SWAT). This is not a fully integrated surface water and groundwater model as are C2VSIM and IWFM, because it does not account for runoff and infiltration processes. However, for planning purposes, it meets the requirements for estimating an overall water balance by month, accounting for seasonal and interannual variability. While the method used to estimate groundwater budget for this study is novel in the peer-reviewed literature, a similar method was used to estimate the economic feasibility of groundwater banking in agricultural land by Rodriguez Arellano (2015).

Background

Groundwater in California

In California, 515 alluvial groundwater basins and subbasins exist that cover 42% of the state (DWR 2015). From these groundwater basins, an estimated 16.5 MAF (million acre-feet) of groundwater is extracted annually, accounting for 38% of the water supply in the state (DWR 2015). Of the 16.5 MAF of groundwater pumped annually, 39% is used for agriculture, 41% is used in urban areas, and 18% is used for the state's wetlands (DWR 2015). The Central Valley alone uses 74% of all extracted groundwater, where the Tulare Lake Hydrologic Region is the greatest groundwater user (DWR 2015).

Several types of long standing groundwater issues exist throughout the state of California. For example, groundwater degradation is observed in the Tulare Basin because of nitrate contamination from dairies, fertilizers, and septic tanks found in the Central Valley (Lund and Harter 2013). Along the coast, seawater intrusion may occur. Coastal basins in the Salinas and Pajaro Valleys have experienced seawater intrusion because of agriculture development (Garza Diaz 2016).

Prior to 2014, not all regions in the state practiced groundwater management. In order to reform groundwater management throughout the state, California Water Code 10933 and 12924 (SGMA 2014) required the California Department of Water Resources (DWR) to prioritize all groundwater basins and subbasins and do groundwater basin assessments, an effort known as the CASGEM (California Statewide Groundwater Elevation Monitoring) Groundwater Basin Prioritization Process (DWR 2014b). Through this effort, the groundwater basins and subbasins were classified as high, medium, low, or very low priority by quantifying the following criteria: a) the population overlying the groundwater basin (an area with underlying permeable material that can store water); b) the projected growth of the population overlying the groundwater basin; c) the number of public supply wells that draw from the groundwater basin; d) the total number of wells that draw from the groundwater basin; e) the irrigated acreage overlying the groundwater basin; f) the degree to which the overlying community relies on groundwater as the primary source of water; g) any documented impacts on the groundwater (e.g., groundwater overdraft, land subsidence, saline intrusion, and water quality degradation); and h) any other information determined to be relevant by the DWR.

Through the CASGEM Groundwater Basin Prioritization Process, 43 groundwater basins were classified as high priority, 84 basins as medium priority, 27 basins as low priority, and the remaining 361 basins as very low priority, as of May 2014 (DWR 2014b). The high and medium priority basins are responsible for 96% of the annual groundwater pumping that occurs in the state of California and provide water supply to 88% of the people residing over those groundwater basins (DWR 2014b). This prioritization analysis identified areas that require the implementation of sustainable groundwater management practices.

Introduction of the Sustainable Groundwater Management Act (SGMA)

In September of 2014, California Governor Jerry Brown signed the SGMA, a piece of legislation intended to manage California's groundwater in a sustainable manner for the first time in history. As part of the timeline for this legislation, groundwater sustainability agencies (GSAs) needed to form by June 2017 and develop groundwater sustainability plans (GSPs) by the year 2020 for critical medium and high priority basins and 2022 for the remaining medium and high priority basins (Christian-Smith and Abhold 2015). Once the GSP has been approved, the GSA has until the year 2040 or 2042 to achieve and maintain groundwater sustainability (Christian-Smith and Abhold 2015). A groundwater basin will be defined as sustainable if none of the six undesirable groundwater related conditions listed by the DWR (SGMA 2014) are evident at the time of evaluation.

Case Study: Ukiah Valley Groundwater Basin (UVGB)

A case study on the UVGB was completed to describe the development of a water budget and to illustrate its utility for water managers developing elements of a sustainable groundwater management plan in a specific basin. This section presents the methodology for estimating a water budget in tandem with how data was collected for each variable. The UVGB was selected since it was classified as a medium priority groundwater basin. According to Bulletin 118, the UVGB has had a relatively stable water table (DWR 2004). Despite there being no evidence of a decrease in the water table, the UVGB is considered medium priority because a value of 15.8 was obtained during the CASGEM groundwater basin prioritization process, in which a basin value greater than or equal to 13.43 but lower than 21.08 determined medium priority status (Figure 1). The high well concentration in the area influenced the UVGB's score of 15.8 (Figure 1). Ultimately, this case study will serve as a generalized example on how water budgets can be done for any groundwater basin since the method presented shows the components of the water budget and the sources of data used.

The UVGB is in Mendocino County in the Russian River Watershed (Figure 2). A GSA has been formed for the UVGB and consists of a group of agencies and individuals representing different stakeholder groups, along with a technical advisory committee. Prior to the formation of the GSA, the stakeholders involved agreed that there was a need to develop a water budget to characterize the groundwater basin and assess the status of the UVGB. The resulting water budget serves as the foundation to create a GSP, inform the GSA on integrated water management strategies to avoid the six undesirable groundwater conditions, and aid in developing monitoring protocols to comply with SGMA expectations.

Water Sources

Surface water and groundwater are used to meet the agricultural and municipal water demands in the UVGB. Surface water sources flow primarily from the Russian River, surface water stored in Lake Mendocino, and from water imported from the Eel River through the Potter Valley Hydroelectric Project (PVHP) (Cardwell 1965). Groundwater sources derive primarily from the UVGB. Communities in Ukiah Valley are groundwater dependent, whereas the communities in Redwood Valley are not. For the purposes of this study, the area in Redwood Valley County Water District is identified as Redwood Valley, whereas the remaining portion of the study area is referred to as Ukiah Valley (Figure 2).

Water Entities

The UVGB has seven major water utilities that provide water supplies to the community: the City of Ukiah, Calpella County Water District, Millview County Water District, Redwood Valley County Water District, Willow County Water District, Rogina Water Company, and the Russian River Flood Control and Water Conservation Improvement District (RRFC) (Figure 3).

DATA COMPONENT RANKING VALUE TABLE

Data Component		Ranking Range (x)	Units	Ranking Value	Confidence Adjustment	Average of Components	Adjusted Ranking Values
1. Population		250 ≤ x < 1000	persons/sq-mi	2			2
2. Population Growth		0 ≤ x < 6	percent	1			1
3. Public Supply Wells		0.25 ≤ x < 0.5	wells/sq-mi	3			3
4. Total Wells		x ≥ 20	wells/sq-mi	5	3.75		3.75
5. Irrigated Acreage		100 ≤ x < 200	acres/sq-mi	3			3
6. GW Reliance	GW Use	0.1 ≤ x < 0.25	acre-foot/acre	2		2	2
	% of Total Supply	20 ≤ x < 40	percent	2			
7. Impacts*		--	--	0			0
8. Other Information**		--	--	1			1
Overall Basin Ranking Score		**13.42 ≤ x <**	--				**15.8**

Overall Basin Priority: Medium

Very Low Ranking Range	Low Ranking Range	Medium Ranking Range	High Ranking Range
Range < 5.75	5.75 ≥ Range < 13.42	13.43 ≥ Range < 21.08	Range ≥ 21.08

Figure 1. Summary of the results obtained for the Ukiah Valley Groundwater Basin as a result of the CASGEM (California Statewide Groundwater Elevation Monitoring) Groundwater Basin Prioritization Process (DWR 2014a).

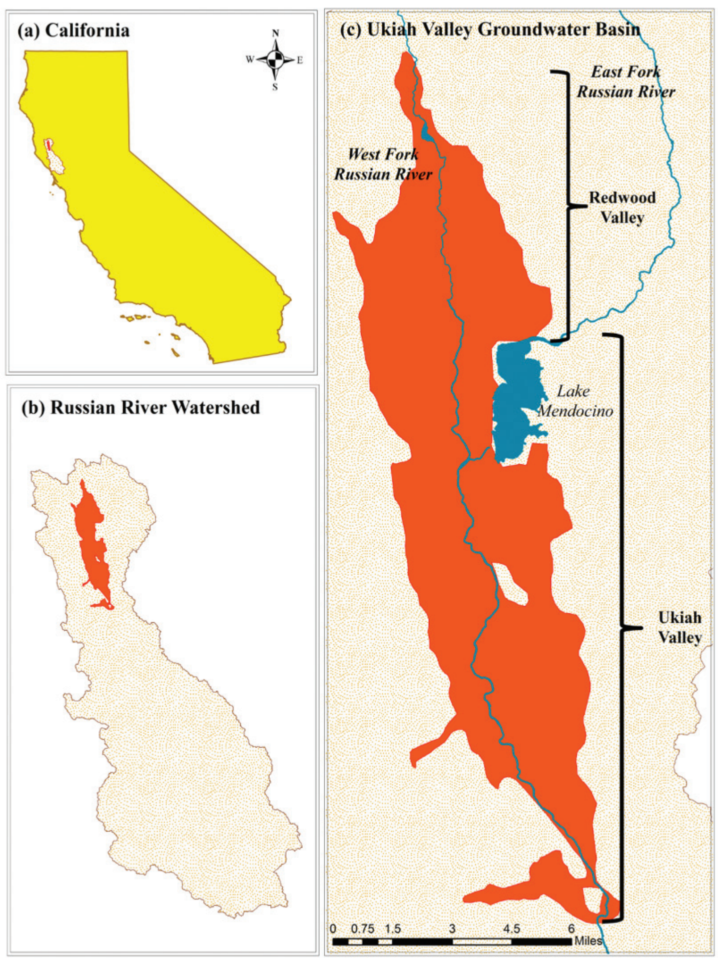

Figure 2. The Ukiah Valley Groundwater Basin (c) located in California (a) and within the Russian River Watershed (b).

Methodology

As a result of data availability, a water budget for the UVGB was developed on a monthly time step from 1991 to 2015. The interactions that occur between the water sources and water supplies in the UVGB are captured in the framework used to develop the water budget (Figure 4). A schematic of the interactions that occur between the water sources and water supplies was developed for the UVGB (Figure 5). Creating the water budget requires four steps. First, calculations associated with the agricultural water demands are estimated to obtain the water use and drainage from agricultural water use, and the recharge resulting from precipitation and irrigation. Second, a surface water mass balance is completed using the continuity equation to estimate the surface water gains and losses. Third, the change in groundwater storage from 1991 to 2015 is estimated. Fourth, a groundwater mass balance is completed using the continuity equation to obtain the lateral groundwater inflows and outflows. The groundwater mass balance utilizes the already calculated variables of recharge from precipitation and irrigation, surface water gains and losses, and the change of groundwater storage.

Agricultural Water Demand Calculations

The monthly agricultural water demand for the UVGB is determined in a monthly time step from 1991 to 2015 (Equation [1]).

$$WD_{ij} = \sum_{k=1}^{K} \left(\frac{(Kc_{jk} * ETo_{ij}) - p_{ij}}{AE_{ik}} * A_{ik} \right) \quad [1]$$

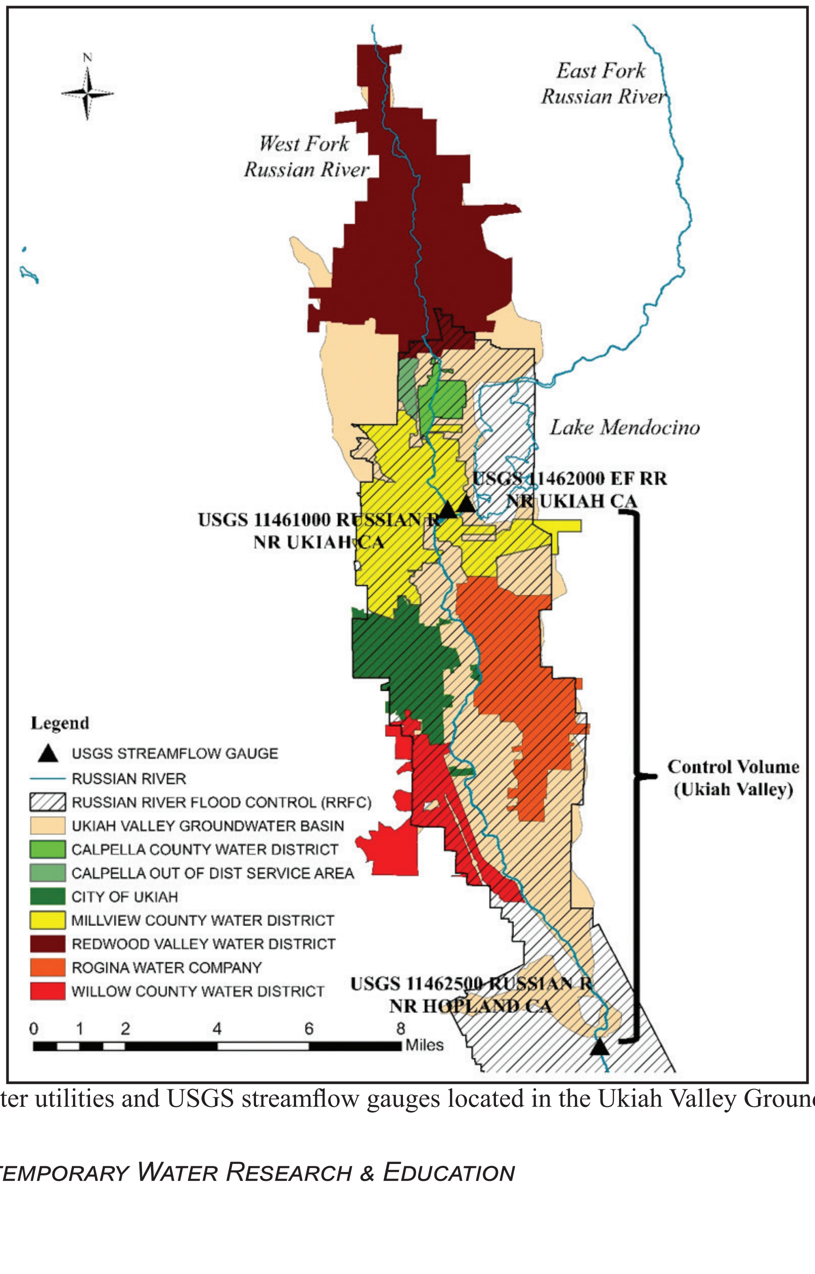

Figure 3. Water utilities and USGS streamflow gauges located in the Ukiah Valley Groundwater Basin.

To estimate the water demand WD_{ij} (AF/month) for a month j and given year i for a crop k, the following inputs were used: acreage A_{ik} (acres), crop coefficients Kc_{jk} (unitless) and application efficiency estimates AE_{ik} (unitless) for each crop, reference evapotranspiration ETo_{ij} (ft), and precipitation p_{ij} (ft). The A_{ik} was obtained from expert consultation (Morse, personal communication 2016). The Kc_{jk} values were obtained from Schwankl et al. (2010) and through expert advice from county advisors of the University of California Cooperative Extension system (Lewis, Harper, and McGourty, personal communication 2016). Reference evapotranspiration (ETo_{ij}) was obtained from the California Irrigation Management Information System (CIMIS) Station 106 in Sanel Valley. Precipitation (p_{ij}) was spatially distributed using the Thiessen Polygon Method using data from the California Data Exchange Center (CDEC) and CIMIS. Application efficiencies (AE_{ik}) were determined using values suggested by Sandoval-Solis et al. (2013) and Lewis et al. (2008). Furthermore, based on expert consultation (Elkins, personal communication 2016), it is assumed that the walnut orchards are dry irrigated and 90% of the grapes are irrigated (Lewis et al. 2008).

The runoff r'_{ij} (ft) that results from a storm event for a given month j and year i, is determined (Equation [2]) and the runoff that results from irrigation r''_{ij} (AF/month) is determined (Equation [3]) in monthly time steps. In both equations, a runoff factor α_{ij} (unitless) of 3% is assumed based on expert consultation (McGourty, personal communication 2016) and from the amount of runoff that was observed during the extent of the project (Fall 2015 to Spring 2017) in the UVGB.

$$r'_{ij} = (p_{ij} - (Kc_{jk} * ETo_{ij})) * \alpha_{ij} \qquad [2]$$

$$r''_{ij} = [WD_{ijk} * (1-AE_{ik})] * \alpha_{ij} \qquad [3]$$

For this study, the soil moisture content is not considered; thus, after the crop water requirement is met and runoff has been generated,

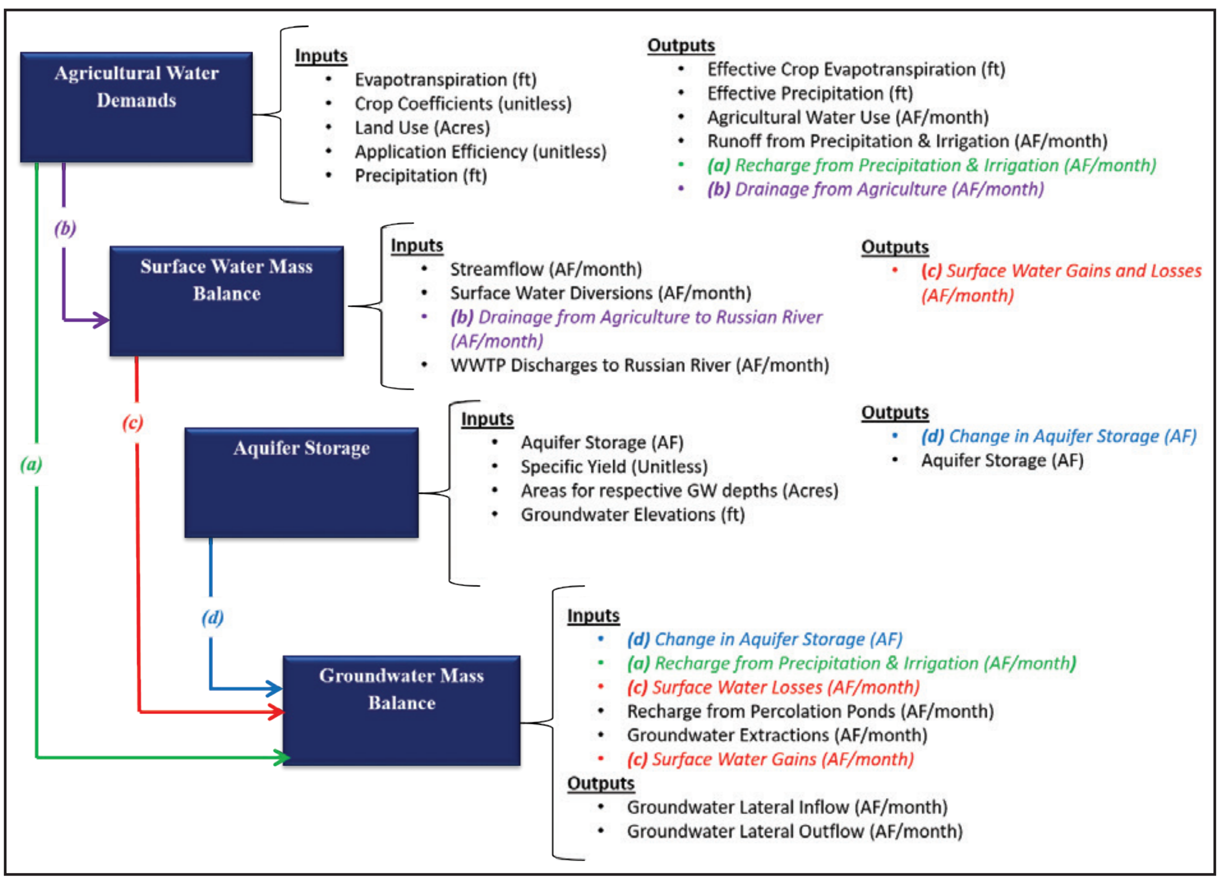

Figure 4. Framework for constructing the water budget.

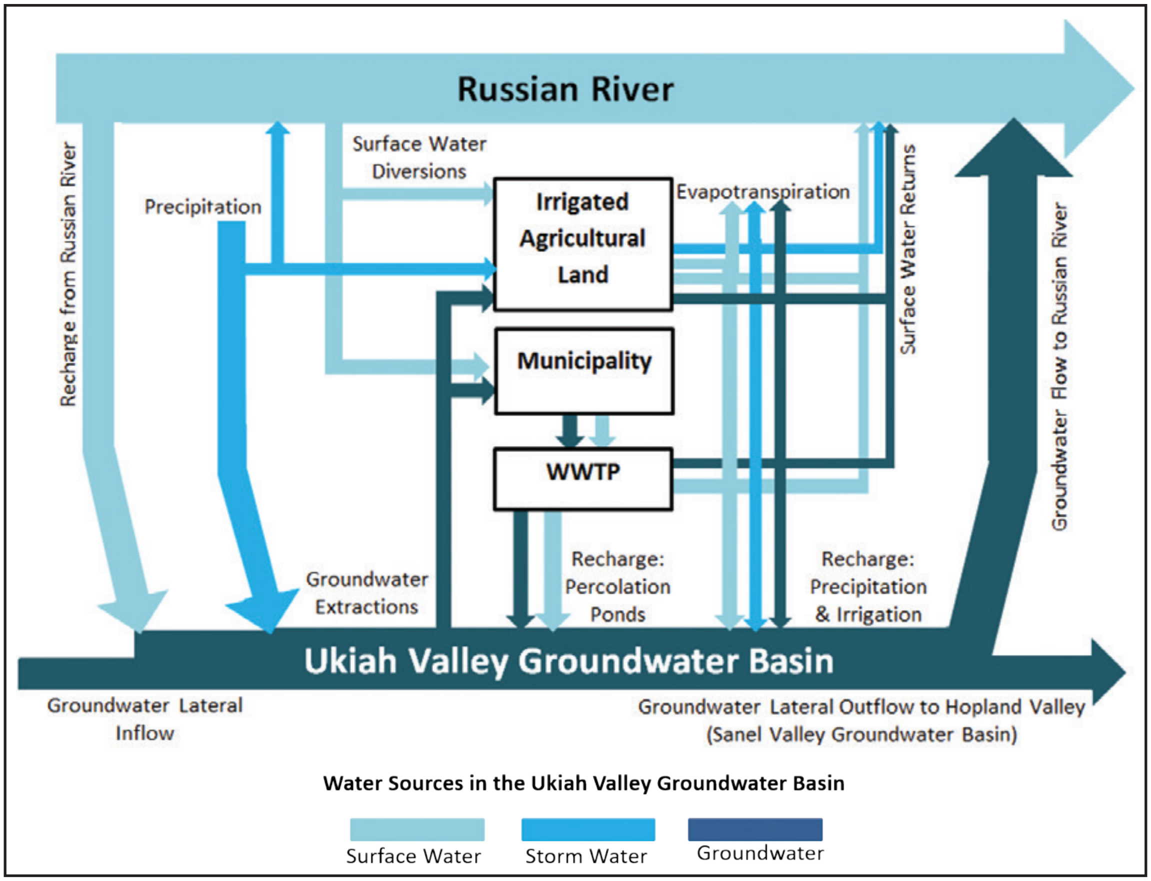

Figure 5. Surface water – groundwater conceptual model for the Ukiah Valley Groundwater Basin.

the precipitation that is in excess percolates into the aquifer. The recharge that occurs because of precipitation RP_{ij} (AF/month) is determined (Equation [4]). Similarly, the recharge from irrigation RI_{ij} (AF/month) is determined (Equation [5]). To estimate the total recharge that results from irrigation and precipitation (R_{ij}) for a given month *j* and year *i* Equation [6] is referenced.

$$RP_{ij} = (p_{ij} - (Kc_{jk} * ETo_{ij}) - r'_{ij}) * A_{ik} \qquad [4]$$

$$RI_{ij} = \sum_{k=1}^{K} [WD_{ijk} * (1-AE_{ik})] - r''_{ij} \qquad [5]$$

$$R_{ij} = RP_{ij} + RI_{ij} \qquad [6]$$

In addition, 3% of the water applied to meet frost protection, post-harvest applications, and heat protection is also assumed to become agricultural drainage, for consistency with runoff from storms and irrigation. The surface water used for frost protection, post-harvest applications, and heat protection is estimated using the information from Lewis et al. (2008).

Surface Water Mass Balance

A surface water mass balance was done to estimate the groundwater–surface water interactions that occurred monthly from 1991-2015 in a control volume. For this study, the *control volume* is the space located between the confluence of the East and West forks of the Russian River near the City of Ukiah [United States Geological Survey (USGS) streamflow gauges for the East Fork and West Fork of the Russian River] and the southern portion of the groundwater basin located near Hopland [USGS stream flow gauge near Hopland], in other words the Ukiah Valley (Figure 3).

For this study, the water budget was done only for the Ukiah Valley portion of the UVGB and not for the entire groundwater basin because there is no streamflow gauge station upstream of Redwood Valley. For the control volume proposed for Ukiah Valley, the surface water inflows (streamflow gauges at the East and West forks of the Russian

River) and the outflow (USGS streamflow gauge at Russian River at Hopland) are well defined.

The surface water mass balance was used to estimate the surface water gains and losses in Ukiah Valley using the continuity equation. The surface water storage that occurs in a determined control volume because of the surface water inflows and outflows is described with Equation [7]. Since no surface water reservoir is considered within the control volume, Equation [7] simplifies to Equation [8]. The term Δt in Equation [7] is change in time. The surface water inflows and outflows in the project area are identified with Equations [9] and [10], respectively. The surface water gains and losses are determined using Equation [12].

$$\Delta Storage_t^{SW} = [Inflow_t^{SW} - Outflow_t^{SW}]\ \Delta t \qquad [7]$$

$$Inflow_t^{SW} = Outflow_t^{SW} \qquad [8]$$

$$Inflow_t^{SW} = Q_t^{WF} + Q_t^{EF} + Return_t^{SW} + Return_t^{GW} + Gains_t^{SW} \qquad [9]$$

$$Outflow_t^{SW} = Q_t^{Hopland} + \sum_{i=1}^{i=1} User_t^{SW,i} + Losses_t^{SW} \qquad [10]$$

$$\sum_{i=1}^{i=1} User_t^{SW,i} = CityUkiah_t^{SW} + Willow_t^{SW} + Millview_t^{SW} + Calpella_t^{SW} + Rogina_t^{SW} + RRFC_t^{SW} + PrivateUsers_t^{SW} \qquad [11]$$

$$Gains_t^{SW} - Losses_t^{SW} = [Q_t^{Hopland} + \sum_{i=1}^{i=1} User_t^{SW,i}] - [Q_t^{WF} + Q_t^{EF} + Return_t^{SW} + Return_t^{GW}] \qquad [12]$$

For the surface water mass balance, the surface water inflows are the West Fork of the Russian River Q_t^{WF} (AF/month) and the East Fork of the Russian River Q_t^{EF} (AF/month). Data from the East Fork of the Russian River were complete up to the year 2011; hence, the remaining monthly values were filled with streamflow data obtained from the CDEC COY station near Lake Mendocino. The surface water returns ($Return_t^{SW}$ and $Return_t^{GW}$) considered are the agricultural drainage and the discharge from the City of Ukiah's Wastewater Treatment Facility (AF/month). The City of Ukiah provided monthly discharge data from 2001-2015 for the Wastewater Treatment Facility, whereas the remaining data from 1991-2000 were estimated using the median value for each month. Finally, the surface water gains $Gains_t^{SW}$ (AF/month), are considered an inflow in the surface water mass balance and an unknown value until solved for (Equation [12]).

For the surface water mass balance, a surface water outflow was the stream flow at Hopland $Q_t^{Hopland}$ (AF/month). Surface water diversions ($\sum_{i=1}^{i=1} User_t^{SW,i}$) resulting from the City of Ukiah, Willow County Water District, Millview County Water District, Calpella County Water District, Rogina Water Co, RRFC contractors, and surface water users with their own water right to divert water for municipal and agricultural water demands were considered a large outflow in the surface water mass balance (Equation [11]). The monthly surface water diversions that occur by each surface water diverter $User_t^{SW,i}$ (AF/month) were either obtained directly from each water entity or were estimated using the median monthly value from the available data records. Finally, the surface water losses $Losses_t^{SW}$ (AF/month) were considered an outflow in the surface water mass balance, an unknown value until solved for (Equation [12]).

Aquifer Storage

Using water table elevations from monitoring wells, groundwater depth contours were created in GIS by using Inverse Distance Weighted Interpolation (Rodriguez Arellano 2015). The water table elevations were obtained from the CASGEM and DWR monitoring wells found in the UVGB from 1991-2015. Groundwater depth contours lines were calculated in GIS in 20-feet increments (*m*). Maps of contour lines were developed from 1991 to 2015 for the months in which there were water table measurements available, usually twice a year. The storage in the UVGB was thus determined (Equation [13]).

$$S_t = \sum_{m=20}^{M} [A_{im} * (d_{mi} - Z)] * \gamma \qquad [13]$$

The S_t term represents the aquifer storage (AF) for the given time step. The term A_{im} is the resulting area (acres) for a given groundwater depth for a given time step. The term Z is an arbitrary reference datum proposed by the authors used to represent the bottom of the aquifer in feet and was proposed to be 490 feet (Rodriguez Arellano 2015). The term d_{mi} (ft) is the groundwater surface elevation with respect to sea level. The obtained soil porosity was assumed to be representative of the whole groundwater basin. The term γ (unitless) is the specific yield, which was assumed to be a value of 8%, a value obtained from Bulletin 118 (DWR 2004) for the UVGB. Once the aquifer storage from 1991-2015 was estimated, the respective change in aquifer storage through time was also determined and ultimately fed into the groundwater mass balance (Equation [17]).

Groundwater Mass Balance

A groundwater mass balance was done to estimate the lateral groundwater inflows and outflows that occur monthly from 1991-2015 in the control volume by using the continuity equation. The obtained results are relevant to Ukiah Valley but are extrapolated to the whole groundwater basin. The groundwater storage that occurs because of groundwater inflows and outflows is described with Equation [14]. The term Δt in Equation [14] is change in time. The groundwater inflows and outflows in the groundwater basin are identified by Equation [15] and Equation [16], respectively. The lateral groundwater gains and losses are determined using Equation [17].

The groundwater inflows considered are the recharge that occurs from precipitation $Recharge_t^{Precipitation}$ (AF/month) and irrigation $Recharge_t^{Irrigation}$ (AF/month), the surface water losses $Losses_t^{SW}$ (AF/month) obtained from the surface water mass balance, tributary recharge $Recharge_t^{Tributary}$ (AF/month) obtained from Flint et al. (2015) for the reach near Hopland, and the recharge that results from the percolation ponds $Recharge_t^{PercolationPonds}$ (AF/month). For this last term, data from the City of Ukiah's Wastewater Treatment Plant and Calpella County Water District's Wastewater Treatment Plant were obtained. Calpella County Water District's Wastewater Treatment Plant percolation rates were calculated given effluent discharge values. The City of Ukiah's Wastewater Treatment Plant percolation rates were obtained from the City of Ukiah for 2009-2015, whereas the percolation rates from 1991-2008 were estimated using the median value for each month. Finally, the lateral groundwater gains $Gains_t^{GW}$ (AF/month) were considered an inflow in the groundwater mass balance and an unknown until solved for (Equation [17]).

For the groundwater mass balance, groundwater outflows include the portion of the agricultural water demands met with groundwater sources $AW_t^{GW,\ crop\ i}$ (AF/month), surface water gains $Gains_t^{SW}$ (AF/month), and groundwater extractions for municipal water demands $GE_t^{Municipal}$ (AF/month) for the City of Ukiah and Calpella County Water District. The municipal groundwater extractions were obtained from the City of Ukiah and from Calpella County Water District. Lastly, the lateral groundwater losses $Losses_t^{GW}$ (AF/month) were also considered an outflow in the groundwater mass balance and an unknown until solved for (Equation [17]).

$$\Delta Storage_t^{GW} = [Inflow_t^{GW} - Outflow_t^{GW}]\ \Delta t \qquad [14]$$

$$Inflow_t^{GW} = Recharge_t^{Precipitation} + Recharge_t^{Irrigation} + Losses_t^{SW} + Recharge_t^{PrecipitationPonds} + Recharge_t^{Tributary} + Gains_t^{GW} \qquad [15]$$

$$Outflow_t^{GW} = \sum_{i=1}^{i=1} AW_t^{GW,crop\ i} + Gains_t^{SW} + GE_t^{Municipal} + Losses_t^{GW} \qquad [16]$$

$$Gains_t^{GW} - Losses_t^{GW} = \Delta Storage_t^{GW} - [Recharge_t^{Precipitation} + Recharge_t^{Irrigation} + Losses_t^{SW} + Recharge_t^{PrecipitationPonds} + Recharge_t^{Tributary}] + [\sum_{i=1}^{i=1} AW_t^{GW,crop\ i} + Gains_t^{SW} + GE_t^{Municipal}] \qquad [17]$$

Results and Discussion

Ukiah Valley Groundwater Basin Agricultural and Municipal Water Demands

From the land use data obtained, the most dominant crops in the UVGB are red wine grapes, white wine grapes, and Bartlett Pears (Morris, personal communication 2016). On average, 8,772 acres of agricultural land are planted each year in the UVGB. The agricultural water demand is on average 10,181 AF/yr. A fraction of this agricultural water demand is applied to meet the crop water needs (8,641 AF/yr) and the remaining fraction is applied for other beneficial uses, such as frost protection, post-harvest application, and heat protection (1,541 AF/yr). The municipal water demand for the UVGB is estimated to be 5,755 AF/yr. The average agricultural and municipal water demand supplied by groundwater is estimated to be 3,411 AF/yr. In contrast, the aquifer recharge from irrigation and precipitation is about 23,011 AF/yr. This number is greater than the total average water demands (municipal and agricultural) supplied with groundwater (3,411 AF/yr) (Table 1).

Table 1. Average groundwater recharge and extractions observed in the Ukiah Valley Groundwater Basin.

Type of Recharge or Extraction	(AF/year)
Precipitation & Irrigation Recharge	23,011
Percolation Pond Recharge, City of Ukiah	2,264
Percolation Pond Recharge, Calpella County WD	42
Average Aquifer Recharge	**25,317**
Ag Water Pumping	2,468
Municipal GW Use	943
Average Aquifer Extractions	**3,411**

In the Ukiah Valley, the agricultural water demand is about 7,789 AF/yr, where 6,635 AF/yr are supplied to meet the crop water needs and 1,154 AF/yr are applied for other beneficial uses such as frost protection, post-harvest application, and heat protection. The total agricultural water demand in Ukiah Valley (7,789 AF/yr) is met with 5,321 AF/yr from surface water and 2,468 AF/yr from groundwater, on average. The municipal water demand in Ukiah Valley is 6,685 AF/yr on average, of which 5,755 AF/yr is met with surface water sources and 930 AF/yr from groundwater sources.

For Redwood Valley, the agricultural water demand is approximately 2,393 AF/yr where 2,006 AF/yr are supplied to meet the crop water needs and 387 AF/yr are applied for other beneficial uses such as frost protection, post-harvest, and heat protection. The municipal water demand in Redwood Valley is 415 AF/yr, on average. The total water demand in Redwood Valley (municipal and agricultural) is met with 2,795 AF/yr from surface water and 13 AF/yr from groundwater, on average. The small groundwater supply in Redwood Valley of 13 AF/yr, came from an intertie well to meet the domestic water demands in Redwood Valley County Water District in the year 2015.

Surface Water Mass Balance

Surface water gains and losses are the primary results from the surface water mass balance. The distribution of the surface water gains and losses varies from month to month (Figure 6). Surface water gains (values above zero, mostly from November to June) are highly variable. Surface water losses (values below zero) occur mostly from July to October. In general, the Russian River mainstem from the confluence of the East and West fork to Hopland is a gaining river from November to June, gaining approximately 18,952 AF/yr, on average. Surface water gains in the Russian River are from: 1) groundwater discharge into the river mainstem when the groundwater table is higher than the surface of the Russian River, and 2) tributary runoff from creeks in the upper watershed and foothills feeding into the Russian River.

In contrast, the Russian River experiences surface water losses of approximately 393 AF/yr from July to October. The surface water losses occur when the groundwater table is lower than the free surface of the Russian River, and recharge from surface water to the aquifer occurs. These results suggest that releases from Lake Mendocino are recharging the UVGB. Given that water from the Eel River is imported into the East Fork of the Russian River via the PVHP, and this water is stored in Lake Mendocino, it is likely that a portion of these water transfers is recharging the UVGB during parts of the year.

Aquifer Storage

Aquifer storage was determined using the water table elevation data for the UVGB from 1991-2015 (Figure 7). In 2003 and 2009, there are dips in the dataset due to questionable water table data records that were available for those given years. Despite the questionable data points, the overall groundwater storage appears stable with time.

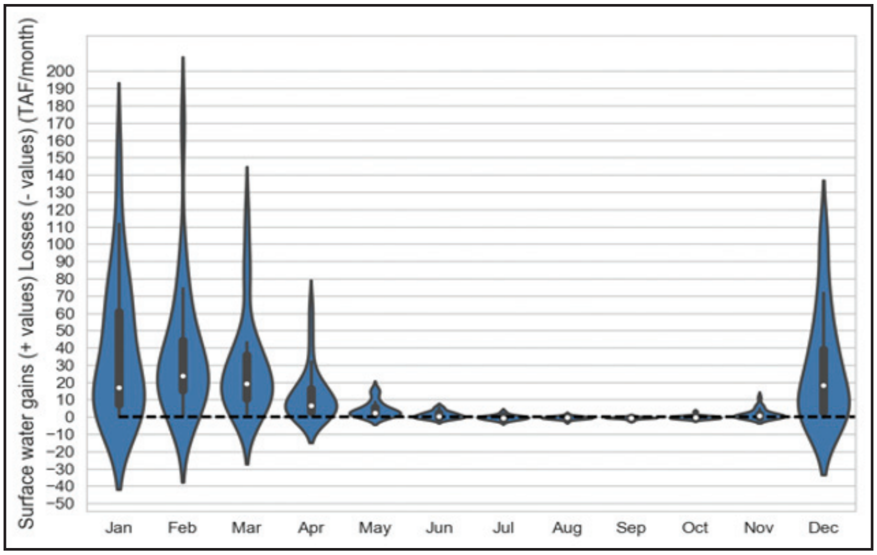

Figure 6. Seasonal distribution of the surface water gains and losses, distribution by year.

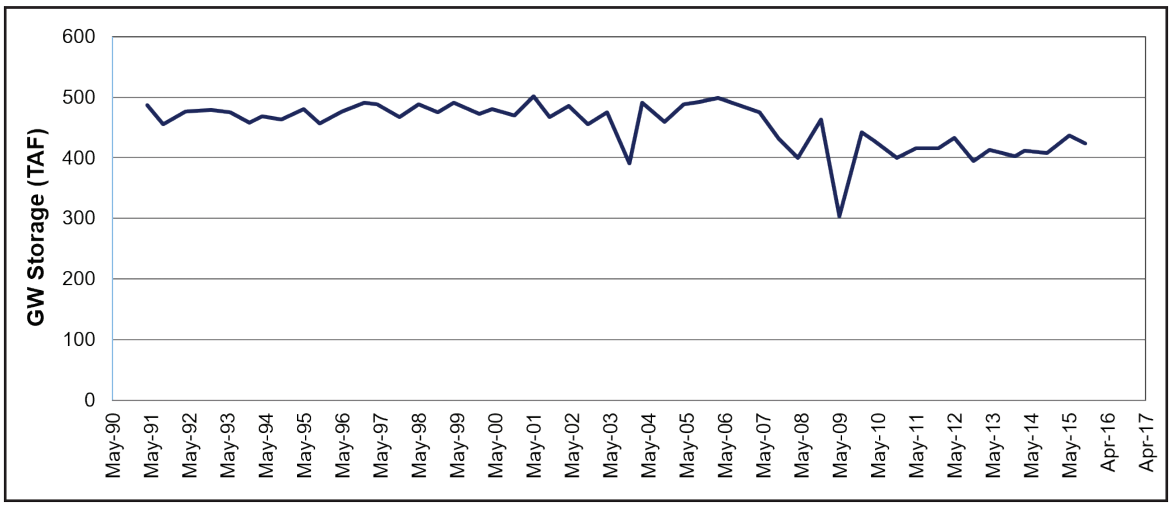

Figure 7. Estimated aquifer storage for the Ukiah Valley Groundwater Basin from 1991-2015.

In the years from 2011 to 2015 there is a subtle decline in storage, but this could be attributed to the drought that occurred from the period of 2012-2015 and from the addition of more water table data.

By plotting the changes in storage (positive and negative) that the aquifer experienced in the time span from 1991 to 2015, a cumulative distribution function from the change in storage observed in the groundwater basin was constructed (Figure 8). Results show that 50% of the time the aquifer experiences a negative change in storage, whereas the other 50% of the time the aquifer experiences a positive change in storage. Ultimately, this means that for the number of times there is a net increase in groundwater storage, there is about an equal number of times there is a net decrease in groundwater storage. Since there is no groundwater storage decline and there is an equal number of times of positive and negative changes of storage occurring, these two observations suggest that the groundwater basin appears to be in balance, concluding, there is no groundwater overdraft in the UVGB. It appears that the amount of groundwater leaving the aquifer is in balance with the amount of water that is recharging the aquifer. These results can be supported with the water table measurements found from the monitoring wells in the UVGB. From those records, it is seen that the water table has been consistently stable with time, showing no evidence of water table lowering.

Groundwater Mass Balance

The lateral groundwater inflows and outflows were estimated through the groundwater mass balance. Given that the groundwater elevation data was available at an interval of approximately every six months, with a measurement recorded in the spring and another in the fall of each year, the lateral groundwater inflows and outflows were calculated at the time interval in which the monitoring well data were available (Figure 9). Results show that the magnitude and occurrence of the lateral groundwater inflows are about equal to the magnitude and occurrence of the lateral groundwater outflows. The lateral groundwater

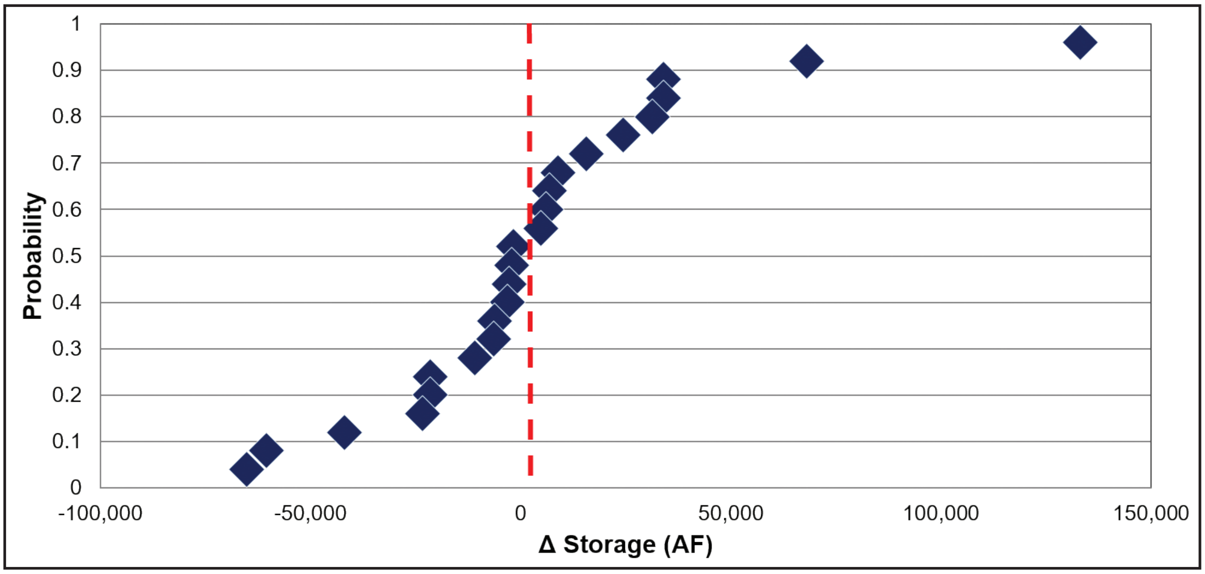

Figure 8. Cumulative distribution function demonstrating the probability of obtaining a particular change in aquifer storage.

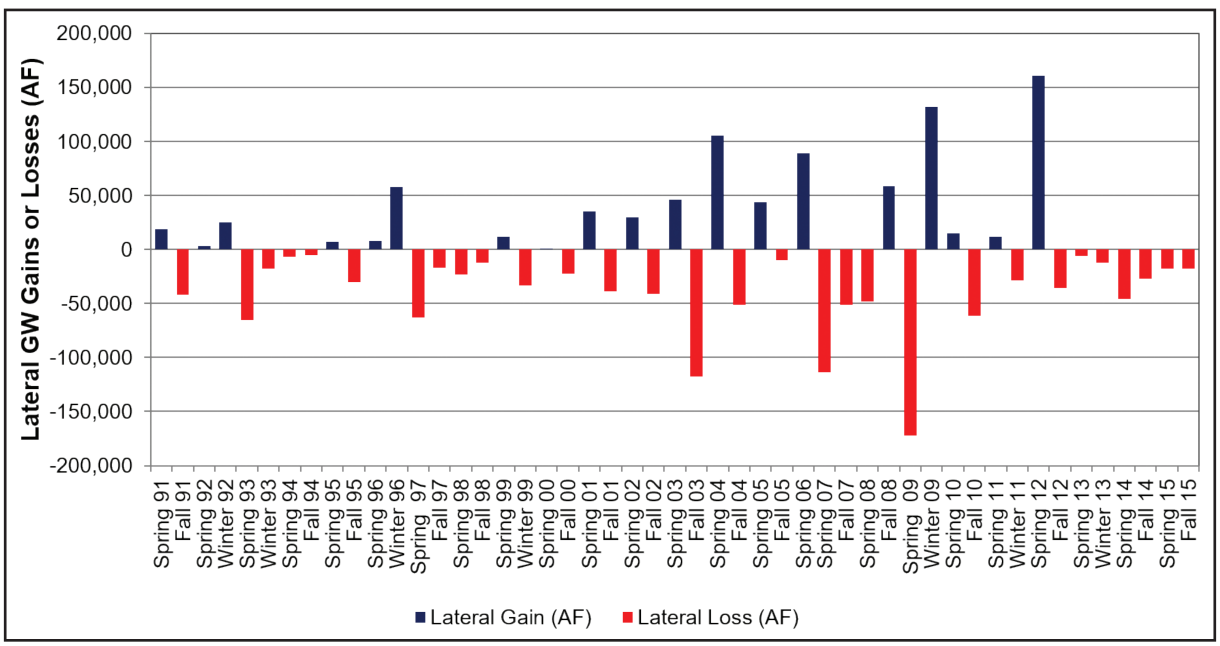

Figure 9. Seasonal lateral groundwater gains and losses in the spring and fall from 1991-2015.

gains observed are assumed to flow from tributary streamflow that recharges the UVGB or from groundwater contributions, such as perched aquifers in the foothills and tributaries of the mainstem. However, it is believed that the driving physical process of the lateral groundwater gains is the result of tributary influence, as suggested by other reports (e.g., Russian River Independent Science Review Panel (RRISRP) 2016). In addition, lateral groundwater losses are occurring. In Farrar (1986) it was outlined that groundwater flows downgradient from the UVGB towards the Russian River, moving from the north to the south end of the groundwater basin. Given the trends previously observed in groundwater movement, the lateral groundwater losses observed are representative of groundwater flowing from the UVGB into the SVGB.

Limitations

Developing a water budget to characterize a groundwater basin is simple, but the quality of the water budget is dependent on the availability and quality of data. The main limitations of this study are related to the control volume used. The control volume centered around Ukiah Valley and not the whole UVGB because there was no active streamflow gauge on the West Fork of the Russian River north of Redwood Valley County Water District. Without an accurate account of the surface water entering the UVGB from the north via the West Fork of the Russian River, the next best alternative was to center the water budget in an area that could effectively account for all the water inflows and outflows. Data gaps were present in some water records, so the missing values were estimated using the median of the data that was available.

Conclusions

Since the UVGB was deemed medium priority, a water budget was established to set baselines for comparison against the six undesirable groundwater conditions the SGMA legislation seeks to prevent. The water budget assessed the status of the UVGB and results indicate that the groundwater basin is not experiencing a decrease in groundwater storage or a lowering of the water table. Surface water-groundwater interactions exist because the Russian River is a gaining river from November to June, gaining on average 18,952 AF/yr, and conversely, a losing river from July to October, losing on average 393 AF/yr. Seawater intrusion is irrelevant to the UVGB since it is inland without risk of saline water entering the fresh water aquifer. Groundwater quality is outside the scope of this study; however, Bulletin 118 (DWR 2004) mentions that the UVGB groundwater quality is generally in good condition. Land subsidence cannot be measured with the results of the water budget but it is assumed that no land subsidence is occurring since the water table has remained stable through time. In addition, groundwater connectivity is observed between the UVGB and the SVGB as a result of lateral groundwater losses identified through the groundwater budget and supported by the work previously done by Farrar (1986). Lateral groundwater gains are also observed to occur, potentially from the SVGB or tributaries. Given these results, it is assumed that tributaries may be the driving force but confirmation of this assumption will require further research.

Overall, the UVGB does not appear to be experiencing any of the six undesirable signs of stress outlined by the DWR. Thus, the basin is in a unique position in which the GSA will have to be proactive in maintaining current basin conditions while also developing an integrated water resources management plan and detailed monitoring protocol for measuring and preventing the six undesirable characteristics that define a groundwater basin as unsustainable.

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Aquifer Depletion in the Lower Mississippi River Basin: Challenges and Solutions

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Abstract: The Lower Mississippi River Basin (LMRB) is an internationally-important region of intensive agricultural crop production that relies heavily on the underlying Mississippi River Valley Alluvial Aquifer (MRVAA) for irrigation. Extensive irrigation coupled with the region's geology have led to significant aquifer decline. The response to the decline has been multi-faceted. Research related to three responses are highlighted: innovation in rice irrigation, on-farm reservoirs, and managed aquifer recharge. Irrigated rice grown in Arkansas, which is nearly 50% of annual U.S. rice production, accounts for a significant portion of aquifer withdrawal. As a result, strategies for using less water while maintaining rice yields are being developed. The Rice Stewardship Partnership (RSP) began in 2015 and aims to improve irrigation management in rice lands of the LMRB. Early results from the RSP are presented. Secondly, on-farm reservoir-tailwater recovery systems (R-TWRS) are increasingly used to store abundant surface water in the LMRB. Over 700 R-TWRS are currently used in rice producing areas of Arkansas. The confining clay layer that overlies the MRVAA in many locations limits rates of aquifer recharge. Locations where the confining layer is thin or non-existent may provide opportunities for artificial (i.e., managed) recharge. A 10-m deep excavation pit from a highway project provided an opportunity to measure infiltration rates of the uppermost section of the alluvial aquifer. Findings from this and other studies are used to demonstrate how conservation, off-season rainfall capture and storage, and managed recharge are being investigated as means to reduce the on-going decline of the alluvial aquifer that is both economically and ecologically important to the LMRB.

Keywords: *Lower Mississippi River Basin, aquifer decline, irrigation, on-farm reservoir, surface water, groundwater*

Agricultural crop production in the LMRB relies heavily on irrigation (Figure 1). Though rainfall is abundant, its timing and quantity often do not coincide with crop needs. Thus, producers have increasingly turned to irrigation to optimize yields and mitigate risks associated with drought (Vories and Evett 2010). Between 2007 and 2012 alone, the amount of irrigated cropland in Arkansas, Louisiana, and Mississippi increased by 7.7, 14.5, and 20.7%, respectively (NASS 2013). As a result, Arkansas now ranks third behind Nebraska and California in terms of irrigated cropland (Figure 1) (NASS 2013). The MRVAA is the primary irrigation water source in the Mississippi-Delta region of Eastern Arkansas due to its accessibility. In Arkansas, groundwater use rates for irrigation have increased more than tenfold from 1950 to 2010 (Kresse et al. 2014). Arkansas leads the nation in rice production, and that crop accounts for approximately one-half of groundwater used in the state (NASS 2013; Kresse et al. 2014).

Agriculture is challenged to increase productivity while using fewer inputs and reducing its environmental footprint. In 2016, approximately 2 million ha soybean, 800,000 ha

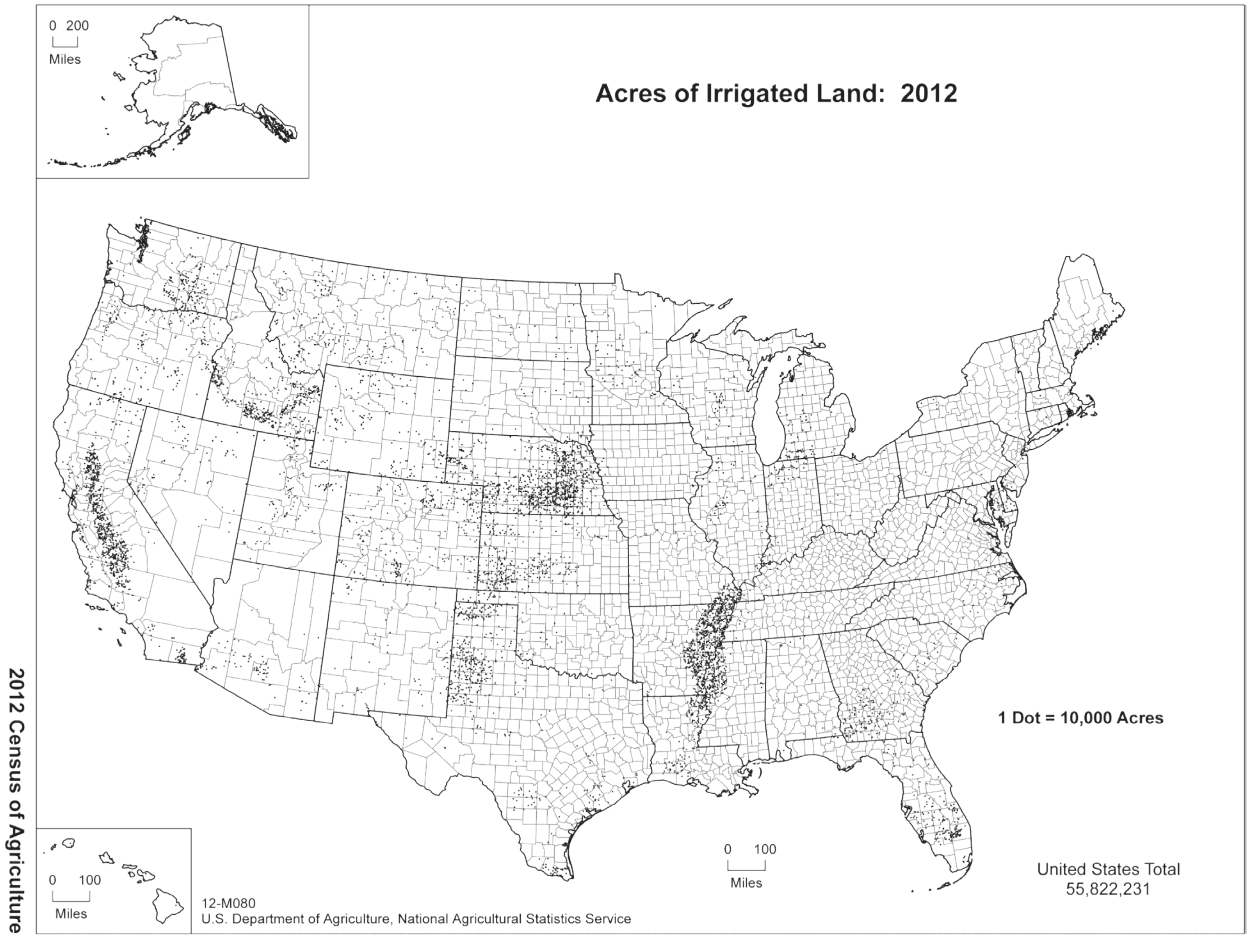

Figure 1. Irrigated land in the United States in 2012 (NASS 2013).

corn, 800,000 ha rice, and 400,000 ha cotton were planted in the LMRB (NASS 2016). Reported evapotranspiration (ET) values for soybean, corn, and cotton grown in the MS Delta are 546, 588, and 552 mm, respectively (Tang et al. 2016), while that of rice was found to vary between 500 to 650 mm (Reavis 2017). In practice, rice receives nearly three times the irrigation that is applied to corn and soybean (Massey et al. 2017). In addition to aquifer decline, excessive irrigation has the potential to contaminate water via surface runoff and/or deep-percolation losses. Hence, improvements in irrigation efficiency are generally expected to not only improve crop water productivity and reduce over-pumping of the MRVAA, but also potentially reduce non-point source pollution.

Groundwater levels in the MRVAA

Groundwater recharge throughout Arkansas primarily comes from precipitation, which slowly infiltrates into the groundwater system. Recharge estimations range from ~ 50 mm yr^{-1} (2 in yr^{-1}) to as little as 10 mm yr^{-1} (0.4 in yr^{-1}) (Broom and Lyford 1981). The 1981-2010 climate normals for Eastern Arkansas are approximately 1200 mm annual precipitation and 16.2°C average temperature (NOAA 2017). Aquifer thickness averages 30 m and tends to decrease moving southward (Ackerman 1996; Pugh et al. 1997). Thicker aquifer sections (up to 48 m) occur in Poinsett County (Pugh et al. 1997). The confining unit of the MRVAA exhibits tremendous spatial variability and varies in thickness (up to 45 m) and occurrence (thick, thin, or absent) across Eastern Arkansas (Gonthier and Mahon 1993).

As of 2015, there were two primary cones of depression in the MRVAA in Arkansas, one east of Little Rock in the Grand Prairie and the other west of Crowley's Ridge (Figure 2a). The depth to groundwater was generated from data collected from 436 spring-measured United States Geological Society (USGS) monitoring wells and interpolated using the natural neighbor method (ANRC 2016). Groundwater level declines have been observed as early as 1929 in portions of the Grand Prairie. The cone of depression west of Crowley's Ridge formed in the 1980s. The sustainable yield of the MRVAA in 2012 was 147 $m^3 s^{-1}$ (3374 Mgal d^{-1}) while withdrawals during that same year were approximately twice that rate (ANRC 2016). Based on model projections, groundwater withdrawals are expected to increase to more than 394 $m^3 s^{-1}$ (9,000 Mgal d^{-1}) by 2050 (Clark and Hart 2009; Clark et at. 2011; Clark et al. 2013; ANRC 2014). Water level declines below one-half of the saturated thickness are forecasted across the MRVAA under current rates of pumping, indicating large areas of depleted aquifer in parts of the Grand Prairie and Cache River Critical Groundwater Areas (CGA) (Clark et al. 2013) (Figure 2b).

Agriculture in the state of Arkansas accounts for one in six jobs and contributed $20.1 billion to the economy in 2012, which is double the national average contribution to state gross domestic product (GDP) (English et al. 2014). Continued aquifer decline has the potential to cause severe negative economic impacts in the future due to the importance of agriculture in the region. Also, streamflow depletion may occur as the aquifer is increasingly disconnected from overlying rivers and streams (Barlow and Leake 2012), causing ecological and economic impacts. These aquifer declines have in some cases led to increased usage of the Sparta, the confined aquifer underlying the MRVAA, for irrigation (ANRC 2016). While this aquifer is mainly used for drinking water in the MRVAA region, further south, a cone of depression that had formed in the more unconfined section of the Sparta resulted in the declaration of the first CGA in Arkansas, the South Arkansas CGA (ANRC 2016).

Addressing Groundwater Declines in the MRVAA

The Arkansas Water Plan consistently calls for additional use of surface water in order to offset groundwater pumping in the state (ANRC 2013). In the Grand Prairie CGA, the U.S. Army Corps of Engineers is constructing two surface water diversion projects: the Bayou Meto Project and the Grand Prairie Area Demonstration Project (GPADP). These projects are intended to support continued irrigation of agricultural crops, while minimizing further aquifer depletion (USACOE 1999). The projects have been under construction since the 1990s and will capture excess surface water from the Arkansas and White Rivers, respectively, to supply and supplement a network of on-farm R-TWRS. Modeling results from the USGS Mississippi Embayment Regional Aquifer Study (MERAS) indicate that when in operation, the Bayou Meto and GPADP will meet approximately 73% and 100%, respectively, of the current groundwater demand of its service area (Clark et al. 2011). Both projects have experienced construction delays owing to environmental-impact concerns and funding hindrances. However, near the Grand Prairie CGA and along the Arkansas River, two irrigation projects have been completed. The first, Plum Bayou, located southeast of Little Rock, was completed in 1993 and serves about 5,750 ha of cropland. The second, Point Remove, located northwest of Little Rock, was completed in 2006 and serves 5,665 ha of cropland as well as 2,430 ha of wildlife refuge. Though smaller than the projects in the Grand Prairie CGA, these provide examples of the potential for successful surface water irrigation systems in the region.

In contrast to the Grand Prairie, no large-scale projects are currently planned for the Cache River CGA owing to a relative lack of surface water resources (ANRC 2016). In the Cache River CGA, producers have increased construction of on-farm R-TWRS. R-TWRS are made up of a complex network of ditches, water control structures, reservoirs, re-lift pumps, and pipelines designed to control and condition water movement. Reservoirs allow winter-spring precipitation to be stored for eventual irrigation use. Research using the Arkansas-specific MARORA economic model

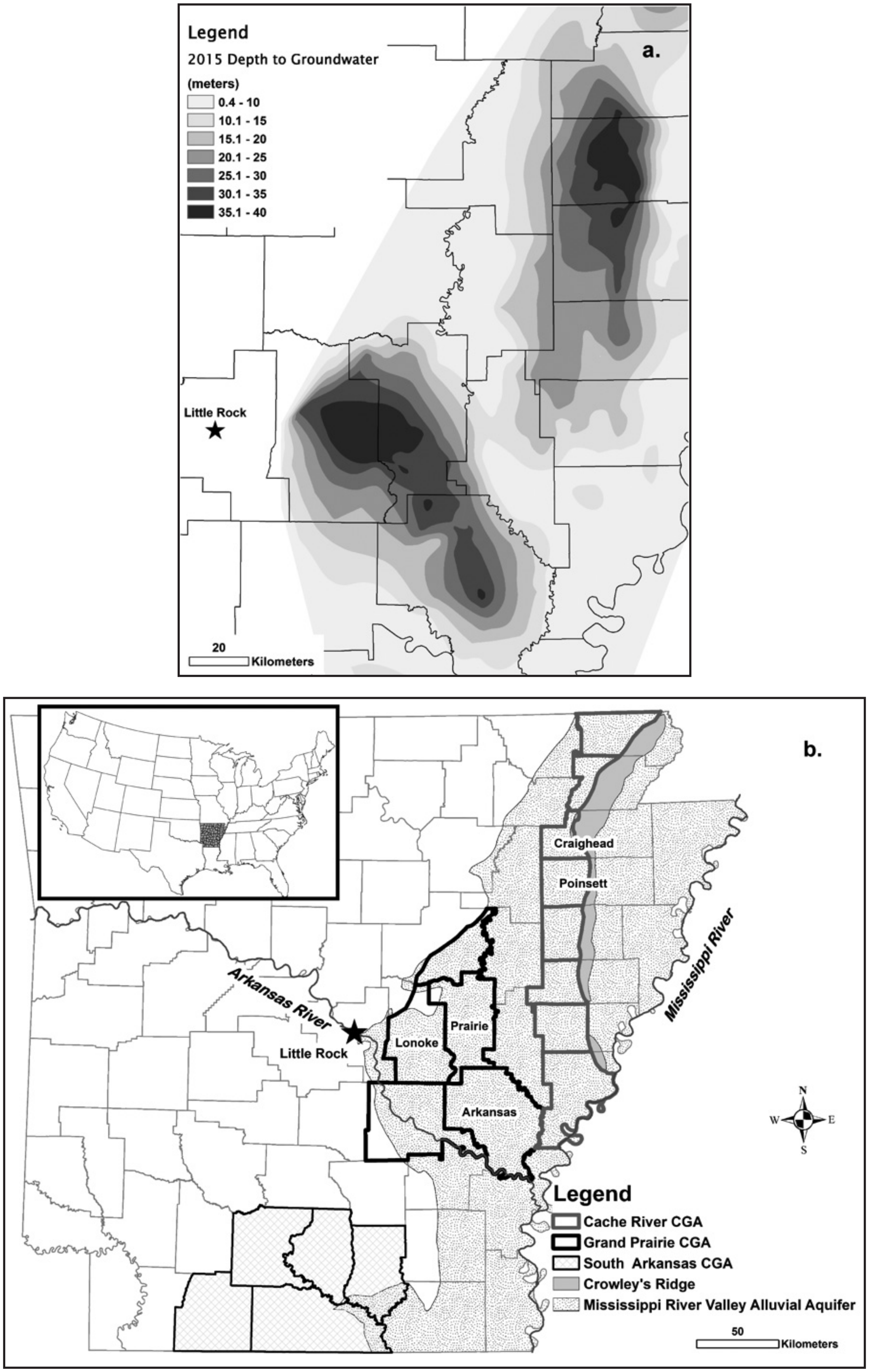

Figure 2. Inset) Location map of U.S. with Arkansas highlighted. a) Depth to groundwater in Eastern Arkansas in 2015 (ANRC 2016). b) Critical groundwater areas (CGA) in Arkansas.

has suggested that as groundwater availability becomes more limited, use of R-TWRS could improve economic returns, especially when combined with water conservation measures that increase irrigation efficiency (Young et al. 2004). In some areas where these systems have been used for over ten years, smaller declines in the MRVAA have been reported compared to those without surface water systems (Fugitt et al. 2011). Little is known about how these systems interact hydrologically with their surrounding landscape, impact water quality, and whether they might play a role in aquifer recharge.

Improving Irrigation Efficiency to Address Groundwater Decline

Evans and Sadler (2008) contend that the "largest potential for basin-wide water savings will likely come from carefully scheduled, reduced irrigation levels." Thus, in addition to efforts to develop new supplies of irrigation water, programs have also been designed to foster conservation practices through in-kind financial support to producers. In 2015, the United State Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) spent $45.86 million on the Environmental Quality Incentives Program (EQIP) (NRCS 2011). The EQIP priorities in Arkansas are to reduce erosion and pollution from animal wastes, improve irrigation efficiency, and reduce dependence on groundwater. Examples of these practices and the associated NRCS conservation practice numbers include irrigation water management (449), cover crops (340), nutrient management (590), irrigation reservoir (436), tailwater recovery (447), drainage water management (554), and grassed waterways (412). Employing computerized hole selection software has improved application efficiency of furrow irrigation through the use of PHAUCET (Pipe Hole And Universal Crown Elevation Tool) which has been updated and made available free of charge to producers and consultants as Pipe Planner software (http://www.pipeplanner.com/). Other related water-saving technologies include remote pump control, surge valves, and various soil moisture sensors that help farmers with their irrigation timing and management decisions.

Rice in the LMRB is grown using a dry-seeded, delayed-flood culture (Wilson et al. 2016) on low permeability soils that reduce deep percolation losses (Snipes et al. 2005). Sizable portions of the LMRB rice growing area have been precision-graded to improve irrigation uniformity (Snyder and Slaton 2001; Walker et al. 2003). Grading to a uniform slope allows use of uniformly-spaced (i.e., straight) levees that divide the field into separate paddies (Snipes et al. 2005). The most common rice flood distribution method is cascade flooding where water is applied to the uppermost paddy and allowed to gravity-flow from one paddy to the next via metal or tarp-style gates installed in the levees. In contrast, multiple-inlet rice irrigation (MIRI) (Tacker et al. 2001; Vories et al. 2005) uses poly-tubing to distribute water to each paddy simultaneously. When properly managed, MIRI reduces irrigation applications by about 25% relative to cascade flooding (Vories et al. 2005; Massey et al. 2017). Additional opportunities exist to improve rice irrigation efficiency and reduce runoff by combining MIRI with intermittent flooding methods (Massey et al. 2014) that were first developed in Asia (Bouman and Tuong 2001; Dong et al. 2001). Intermittent rice flooding, also known as alternate wetting and drying (AWD) has been shown to reduce field runoff by nearly 50% (Martini et al. 2013).

Agricultural production, particularly rice cultivation, is responsible for a significant portion of global anthropogenic greenhouse gas (GHG) emissions (Ciais et al. 2013). Additionally, rice cultivation has a higher global warming potential (GWP) than other cereal crops (Linquist et al. 2012), largely due to methane (CH_4) emissions associated with continuous flooding. Changing water management strategies may help address both GHG and water issues. Currently, the most prominent strategy to accomplish this is AWD. AWD was developed at the International Rice Research Institute (IRRI) as a water-saving technology to help Asian farmers cope with water scarcity (Bouman et al. 2007). This practice has been adapted across Asia to reduce water usage and CH_4 emissions. In the U.S., research has been conducted under a range of conditions and scales (Linquist et al. 2014; Massey et al. 2014). AWD has been found to reduce GHG emissions through reductions in CH_4 (Linquist et al. 2012).

Case Studies

Three case studies are described that highlight efforts to reduce aquifer depletion through improved irrigation management, expanded surface water use, and managed aquifer recharge.

Rice Irrigation

The Regional Conservation Partnership Program (RCPP) began with the 2014 U.S. Farm Bill legislation. The Rice Stewardship Partnership (RSP) RCPP is a collaboration among USDA-NRCS, Ducks Unlimited (DU), and the U.S. Rice Federation (USRF) that began in January 2015. DU provides the project management while the USRF provides coordination with all activities conducted through the EQIP and the Conservation Stewardship Program (CSP). The funds provided through the RCPP were divided between the rice producing states of Arkansas, California, Louisiana, Texas, Mississippi, and Missouri in proportion to the total amount of rice each state contributes to national total production. Each state set priorities focused on water conservation, nutrient management, and wildlife habitat enhancement.

The RSP in Arkansas focused on water management, nutrient management, and waterfowl habitat. It was designed to address the issues of day-to-day water management issues rather than water management infrastructure (e.g., land leveling, on-farm reservoir construction, drainage pipes). This plan was defined at three levels of irrigation water management (IWM): basic, intermediate, and advanced. At the time the RSP was initiated there were no farmers enrolled beyond the basic IWM plan.

Of the 270 applications, a total of 70 contracts were awarded. A majority of these contracts were made at the intermediate IWM plan. In this plan the grower must: 1) irrigate using a scheduling program of their choice; 2) keep records of all irrigations and all calculations that lead to decisions concerning irrigation timing and amount; and 3) provide copies of these irrigation records and a written plan that evaluates the irrigation process for the season with a proposal on what improvements will be implemented for the next season to improve irrigation strategies on the contracted land. The grower must select three of the following options: a) determine soil moisture via in-field sensors (or water depth rice paddies) equipped with data loggers that can be manually downloaded by the operator; b) install permanent or portable manual flowmeters to obtain irrigation flow rates and volumes applied throughout the growing season; c) maintain either an electronic or written record for each irrigation cycle, where duration and volume are recorded for each field under contract; d) install a weather station at the farm level to record temperature, rainfall amount, and windspeed; e) use a surge valve to improve irrigation efficiency; f) utilize software such as computer hole selection (i.e., PHAUCET or Pipe Planner); and/or g) implement AWD (includes row-rice cropping). A majority of the farmers enrolled under this program selected a, b, d, and g.

By June 2016 it was estimated that a total of 29,298 ha of rice was contracted under this project in the mid-south, with the majority of the projects occurring in Arkansas. On approximately half of this land, IWM was initiated and included AWD. Initial data collected from the contract reports from these fields indicated a reduction in the amount of water applied. All contracted fields from 2016 were included in the 2017 season, with additional fields being added through the NRCS-CSP program that was introduced in 2017. An additional $7 million was awarded to the RSP at the end of 2016. These funds were again targeted to the mid-south rice production areas in Arkansas, Mississippi, Louisiana, and Missouri to further implement water conservation, nutrient management, and wildlife habitat enhancement.

On-farm Reservoirs-Tailwater Recovery Systems

Agricultural drainage ditches linked to a surface water storage reservoir are often used as a contiguous system to recycle surface water in areas of aquifer decline and to limit off-farm nutrient and sediment transport. The systems are designed to accumulate, store, and allow the reuse of irrigation tailwater and rainfall runoff. As such, they can provide improved efficiency of irrigation and positively affect water quality, while reducing costs through a reduction in deep groundwater pumping (Young et al. 2004). While farmer-based initiatives and government-subsidized programs have led to the wide-spread construction of these systems, the actual numbers and sizes of the reservoirs are not known. For this reason, a remote sensing inventory using the most recent year of imagery provided by the National Agricultural Imagery Program was conducted to determine the number, surface area, and location of on-farm irrigation reservoirs present in the primary counties of the Grand Prairie CGA and the Cache River CGA (Figure 2b) (Yaeger et al. in press).

Overall, the Grand Prairie CGA had approximately 4.5 times as many reservoirs and total reservoir surface area as the Cache River CGA. The 632 reservoirs totaling 9,336 ha surface area in the Grand Prairie CGA were clustered mainly in the northwestern portion of Arkansas County, southwestern Prairie County, and the central portion of Lonoke County. The 143 reservoirs totaling 2,019 ha surface area in the Cache River CGA were mainly located throughout Poinsett County and in southern Craighead County.

In the Grand Prairie CGA, reservoir size distribution was consistent among the three counties, with the most common size being 5-10 ha, followed closely by 10-20 ha. Less consistency was observed in the Cache River CGA. In Poinsett County, 10-20 ha reservoirs were most common, followed by 5-10 ha. In Craighead County, small reservoirs (1-5 ha) were most common. Large reservoirs (>60 ha) were found in Arkansas and Prairie Counties in the Grand Prairie CGA, and in Craighead County in the Cache River CGA. In both regions, these larger reservoirs were a small proportion (<3%) of the total number of reservoirs.

Managed Aquifer Recharge

A managed aquifer recharge experiment was conducted to determine if an infiltration basin could augment local groundwater recharge in the Cache River CGA. In 2015, the highway department contracted sand excavation of unfarmed land owned by a collaborating producer. This excavation pit would serve as a test case to measure the rate of infiltration into the MRVAA using nearby surface water as the recharge source. Prior to excavation, soil core analyses revealed soil properties within the confining clay layer of red-brown clay and silty clay soils (0-3.7 m deep) with sand below. Once excavation was completed to a depth of about 6 m, the uppermost-unsaturated section of the MRVAA, consisting of well-sorted medium-grain size sand, was exposed and free of the confining clay layer. The excavation pit was about 27 m above the existing water table, and this unsaturated aquifer section could be utilized to improve water quality of infiltrated water by soil aquifer treatment (SAT) through a combination of physical, chemical, and biological processes (Bouwer 1991). The excavation pit was used to conduct an experiment to measure infiltration rates of water pumped from a surface water source through the unsaturated zone above the water table.

The experiment began with instrument installation in early February 2016 and ended June 2016. Submersible pressure transducers were installed at the bottom of the excavation pit to monitor water level changes. Two staff gauges, associated with automatic game cameras, were installed on the north and south sides of the pit to visualize the water level depth once the excavation pit was filled. Another pressure transducer was deployed in an irrigation well 0.3 km away to monitor groundwater levels. To measure the components of the water budget, an on-site weather station was set up to collect meteorological data of air temperature, precipitation, relative humidity, wind velocity, and evaporation rate. Sediment samples from the excavation pit floor and sidewalls were collected pre- and post-experiment for analysis of organic matter, soil texture, and sand composition. Prior to adding water, the pit's location and elevation were determined so that changes in groundwater storage could be estimated.

Input water from a nearby surface water source was pumped through an underground pipe to a riser and delivered to the excavation pit via plastic irrigation tubing. Beginning 5 February 2016, water was pumped into the excavation pit continuously for 24 hours, representing a volume of 4.2 ML. Total precipitation during the experiment was 593 mm. This was 47% of the 30-yr climate normal (NOAA 2017). Two large precipitation events occurred on 8-10 March 2016 and 30-31 March 2016, totaling 100 and 152 mm, respectively.

Analysis of water level data indicated continuous infiltration throughout the experiment with water levels rising only following precipitation. Major precipitation events in March 2016 raised water levels to about half of the initial water input. An initial infiltration rate of 188 mm d^{-1} and 191 mm d^{-1} was measured at two locations and both values exponentially decreased until March 2016, with rates varying between 0-120 mm d^{-1}. Groundwater levels fluctuated approximately 0.3 m during the experiment; however, the extent of recharge and the relationship between change in excavation pit water level and groundwater level are not clear. Expanded monitoring near the pit and through the full-unsaturated zone would be required to confirm if excavation pit water level changes corresponded directly to groundwater fluctuations. Using the infiltration rate calculated from one of the pressure transducers and an initial excavation pit floor surface area of 0.17 ha, the total groundwater storage increase was 8.8 ML (7.2 acre-feet), more than double the initial water input.

These results suggest that infiltration basins warrant further study as a means to help offset groundwater decline. For example, fourteen exposed borrow pits have been identified within Craighead County (Yaeger et al. in press). With the permission of landowners, these existing excavation pits might be rehabilitated to act as infiltration basins, with the assumption that they are at a depth below the confining layer and are suitably permeable to allow recharge. Removal of the bottom surface of these pits might be necessary as debris and/or silt may have accumulated over time to form layers that decrease infiltration (Bouwer and Rice 1989). Unless widely adopted, managed aquifer recharge would not address the region-wide challenges of groundwater decline in eastern Arkansas, but has the potential to augment local groundwater recharge in the Cache River CGA and merits further research.

Conclusions

Agriculture in the LMRB relies heavily on the MRVAA for irrigation. Declines in the aquifer necessitate improved management of water resources in the region. Three case studies that aimed to mitigate aquifer decline were described. An effort to improve rice irrigation management in the LMRB through several collaborating partners as part of the Rice Stewardship Partnership was found to reduce the amount of water applied on nearly 30,000 hectares. An inventory of on-farm reservoir tailwater recovery systems shows that significant investments have been made as part of efforts to use more surface water in critical groundwater areas. Lastly, a novel test of managed aquifer recharge was described that will be used as the basis for further testing of this approach in areas where large-scale surface water projects are unlikely. It is anticipated that the case studies described will impact the long-term sustainability and resiliency of water resources in the region.

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General questions about the conference can be directed to Karl Williard (williard@siu.edu), Executive Director of UCOWR, or Staci Eakins (ucowr@siu.edu), Administrative Assistant.

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